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DISTANCE AND CARRIER-CURRENT RELAYING SYSTEMS OF HIGH-VOLTAGE TRANSMISSION LINES

by
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Discussed in this paper are both distance and carrier-current protective relaying devices used in the USSR. In the first part of the paper the field of application of distance protection in the USSR is defined and the various types of resistance relays in use are described as well as electric interlocking intended to prevent faulty action of distance protection devices in case of power swings in the system or faults in the voltage circuits.

In the second part of this paper the principles of the directional and phase-differential types of carrier-current protective relaying developed in the USSR are discussed and the particular features of the devices involved are noted relative to their use for the protection of the 400-kv lines under construction.

INTRODUCTION

Distance protection and carrier-current relaying are both widely used on high-voltage transmission lines. Distance protection belongs to a few types which without the aid of carrier channel or any other connection channel secure a selective isolation of faulted line sections and the backing up of the adjacent undamaged section in a complicated network with a large number of power-supply sources. In carrier-current relaying high frequency currents are used to coordinate the operation of protective sets at the two ends of the protected line. Protective devices of this type are blocked for short circuits outside of the protected zone and therefore secure quick isolation of the line whenever a short circuit occurs at any of its points.

In the USSR carrier relaying and distance protection devices are arranged in separate complete units. Separate arrangement is always far more convenient in operation than a combination of both types in a single set.

As power systems in the USSR grow in capacity and the automatic forced excitation of synchronous machines becomes widespread, remote short circuits produce ever diminishing voltage drops at junction points of a network, thus affecting less the operation of the system. As a result of this development, the relay protection of transmission lines can, in many cases, be considerably simplified and, in particular, carrier-current relaying can be dispensed with. In every case where distance protection within the time lag of the first zone secures the isolation of all phase-to-phase short circuits, producing a voltage drop apt to disturb the

operation of the system, no carrier-current relaying is provided, and distance protection is used both as main and back-up protection.

If carrier relaying devices are installed for back-up protection, often instead of distance protective devices simple overcurrent instantaneous cut-offs are used in conjunction with overcurrent directional relays which may be used if they secure the isolation of faults with a time lag of not above 0.6 sec.

I. DISTANCE PROTECTION

At present, a great number of varied distance relays home as well as foreign made are in service in the USSR.

The accumulated operating experience has made it possible to appraise them and to define reasonable ways and principles for further developments in the field of distance protection.

Long-year practice has shown that it is not expedient, as a rule, to use distance protection for clearing every kind of short circuit, the single-phase faults inclusive. Neither is it good to use separate distance devices for single-phase faults. This leads to a more complicated protection scheme, which can hardly be justified because with faults of this kind a reliable selective isolation will in all but exceptional cases be secured by simple overcurrent directional relays*. It is only in some complicated networks, where taking account of actual conditions we must expect small currents and large fault resistances to arise in case of ground fault, that the use of reactance relay protection seems reasonable. This kind of protection involving a compensation scheme for a total drop of voltage in the protected zone was designed in the USSR in 1940 and has since been used with success on several 110- and 220-kv lines.

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* These are then made as three-step devices and have characteristics analogous to those of distance protection devices.

Generally distance protection in the USSR is arranged to operate in response to polyphase short circuits.

As starting elements, in networks with a large ground fault current, directional resistance relays are mainly used whose characteristic in a complex plane with R and X axes has the form of a circle passing through the origin. This type of relay best meets the basic requirement which the starting elements are intended to satisfy, namely they must not be responsive to changes in the input resistance of the line under normal operational conditions (Fig. 1). Compared to other types, these relays

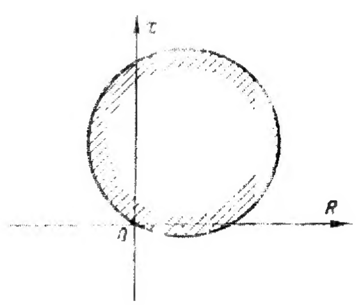

Fig. 1. Characteristic of directional resistance relay (operation zone of relay is shaded).

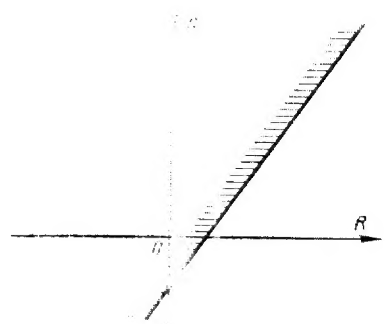

Fig. 2. Characteristic of phase-limiting relay (operation zone of relay is shaded).

are also less responsive to power swings. If more perfect restraint for overload and swinging is needed, phase-limiting relays are inserted in addition (Fig. 2).

In networks with a small ground fault current where the loads, as a rule, are smaller while the importance of fault resistances is higher, impedance relays are used as starting elements of the protection system or current relays wherever possible.

For distance elements measuring the length of the protected zone impedance relays, reactance relays and directional resistance relays have mainly been used up to the present. Yet reactance relays are gradually coming out of use because of their complexity and be-

cause they may possibly operate not selectively on two feeder lines due to some feeding of fault resistances.

In order to diminish the influence of fault resistances on the operation of impedance relays a shifting of the characteristic of these relays and the fixation of their short-time setting (Fig. 3) are practised.

For a reduction of the influence of transient conditions in the primary circuits *1* and in the protection circuits *2* and for the elimination of a dead zone the protective relaying schemes have resonance circuits in the relay-winding circuits.

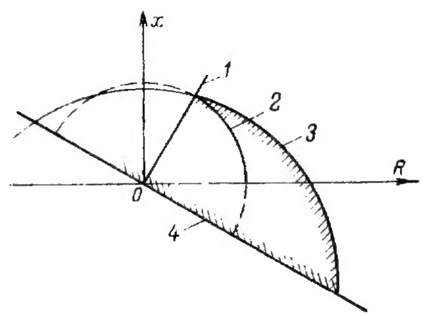

Fig. 3. Characteristic of directional distance protection with impedance relay.

1 — resistance of protected line; *2* — operation zone of an impedance relay; *3* — operation zone of a resistance relay with displaced characteristic; *4* — operation zone of a directional power relay. Shaded is the operation zone of the protective equipment including a directional power relay and a resistance relay with a displaced characteristic.

Most of the distance relays in the USSR are based on the four-pole induction relay with a cylindrical rotor. This system permits most varied characteristics to be obtained in a rather simple way and also provides the possibility for an independent regulation of the main relay parameters. It is only when requirements for sensitivity, operation speed and other parameters are exceptionally high that some other types of magnetic systems and other relaying schemes are used. Several of these relays are discussed below.

Of late a new type of relay has become widespread. It operates in response to any two-phase fault at a point. This is a polyphase compensation relay designed in the USSR in 1945.

Its torque is defined as

$$M = K|\dot{U}_{AB} - \dot{U}_{KAB}||\dot{U}_{CB} - \dot{U}_{KCB}|\sin\alpha \qquad (1)$$

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where

$\dot U_{AB}$ and $\dot U_{CB}$ — interphase voltages at the site where the protective device is installed;

$\dot U_{KAB}$ and $\dot U_{KCB}$ — "compensation" voltages understood to be equal to voltage drops corresponding to differences between the respective currents through the resistance of the protected line section to the end of the protected zone;

φ — angle between the vectors of the resultant voltages put in brackets.

The expression of the relay torque in terms of symmetrical components has the form

$$M = K[\dot U_2 - \dot I_2 Z_p] \cdot [\dot U_1 - \dot I_1 Z_p] \sin \varphi \qquad (2)$$

where

$\dot U_1$, $\dot U_2$, $\dot I_1$ and $\dot I_2$ = respectively the voltages and currents of positive and negative sequences at the site where the protective device is installed;

Z_p — impedance of the protected line section to the end of the protected zone.

For the sake of simplification this relay, too, is designed as a four-pole induction system with a cylindrical rotor; its main properties are as follows:

a) It operates correctly for any phase-to-phase fault without any switching in current or voltage circuits; thus, it replaces three distance relays inserted separately for each phase.

b) It is of instantaneous directional type and has no dead zone with regard to voltage.

c) It also operates correctly for most ground faults at a point where any two phases are involved. Only with very large setting values and very large fault currents may this relay fail to operate for short circuits in the protected zone. But this should not be regarded as an essential drawback since analysis shows that failures are possible

only with such network parameters and such fault currents which permit a selective overcurrent instantaneous cut-off of zero sequence operating with a wide margin of sensitivity to be installed on the protected line.

d) The relay is inoperative for symmetrical conditions, hence for such power swings and overloads as are not attended by non-symmetrical short circuits. Therefore, using it as a distance protection element of the second zone we can dispense with interlocking elements for power swings and block these relays only in individual cases while using them for the first zone.

e) The relay is most sensitive and operates at high speed, having an equal consumption with directional resist-

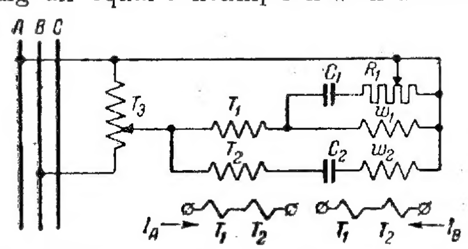

Fig. 4. Schematic diagram of impedance relay.
w_1 and w_2 — induction relay windings; T_1 and T_2 — transformers with air-gapped magnetic cores; T_3 — potential autotransformer; R_1 — added resistance; C_1 and C_2 — condensers.

ance relays. The minimum currents for which the error of the relay is not above 10 per cent are several times smaller.

f) On short lines, where the relative values of fault resistances are particularly great, the relay becomes inoperative at higher resistance values compared to impedance relays and directional resistance relays.

On account of the important advantages of this relay its field of application has been widening from year to year.

Like in several other types of relay, the influence of transient conditions in the compensation polyphase relay is reduced by inserting resonance circuits in the relay winding circuits. The schematic diagrams of the polyphase compensation and that of the impedance relays are represented in Figs. 4, 5 and 6.

Alongside of induction directional resistance relays some-

times supplemented with phase-limiting relays other types have of late been coming to use on long heavily loaded lines, namely: detective directional resistance relays and several types of relays with special characteristics—elliptical, oval, with sliding compensation, and others.

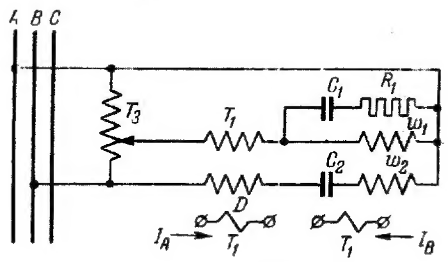

Fig. 5. Schematic diagram of directional resistance relay.
w_1 and w_2—induction relay windings; T_1—transformer with air-gapped magnetic core; T_3 — potential autotransformer; R_1 — added resistance; C_1 and C_2—condensers; D—choke.

Detective schemes permit sensitive d. c. relays to be used as operating elements of the protective arrangement, such as electromagnetic relays with a closed magnetic circuit (relays with armature release), polarized relays, etc.

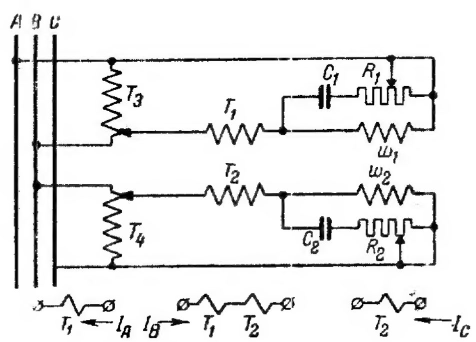

Fig. 6. Schematic diagram of polyphase compensation distance relay.
w_1 and w_2 — induction relay windings; T_1 and T_2 — transformers with air-gapped magnetic cores; T_3 and T_4 — potential transformers; R_1 and R_2 —added resistances; C_1 and C_2—condensers.

The torque of the detective directional resistance relay is defined as

$$M = K\left\{\left|\frac{\dot{I}Z_{p.s.}}{2}\right| - \left|\dot{U} - \frac{\dot{I}Z_{p.s.}}{2}\right|\right\} \qquad (3)$$

where

$\dot{U}$ and $\dot{I}$ = voltage and current at the site of the protective arrangement;

$\dot{Z}_{p.s.}$ = impedance of the line section to the end of the protected zone.

Fig. 7 represents a schematic diagram of the directional resistance relay with armature release, designed in the USSR in 1951.

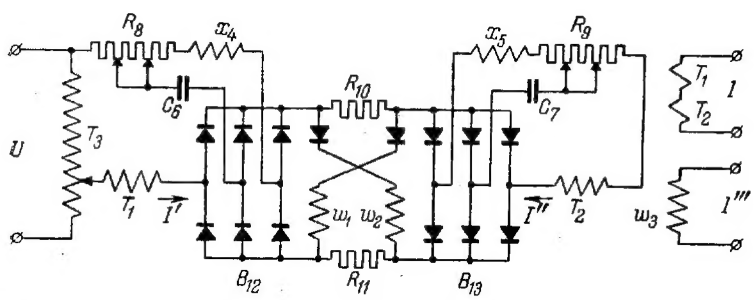

Fig. 7. Schematic diagram of detective directional resistance relay based on armature release.

w_1 and w_2 — windings of armature-release relay; U and I — voltage and current applied to the circuit; $I''' = \frac{dI}{dt}$ — current in the relay releasing system proportional to the rate of variation of the applied current; T_1 and T_2 — transformers with air-gapped magnetic cores; T_3 — potential autotransformer; x_4 and x_5 — chokes; C_6 and C_7 — condensers; R_8, R_9, R_{10} and R_{11} — added resistances; B_{12} and B_{13} — rectifiers.

The protective arrangement receives voltages and curents of the re spective phases. In the setting regulation scheme the currents are transformed into two compensation voltages of equal magnitude:

$$\dot{U}' = \frac{\dot{I}\,\dot{Z}_{p.s.}}{2}\ .$$

One of them is applied directly across the rectifying and smoothing circuit while the other is first subtracted from the residual voltage $K_1\dot{U}$ and then is likewise supplied through a separate rectifying and smoothing circuit.

Currents $\dot{I}'$ and $\dot{I}''$, that flow at the output of these circuits, are proportional to the input voltages. The currents are compared by a special bridge circuit, which excludes

the possibility of mutual influence of the rectified currents and through a rectifier are conveyed to the operating element of the relay with armature release.

This relay has two magnetic systems: an operating (retaining) system with a closed magnetic circuit and a ground armature and a releasing (repulsing) system which in the event of a short circuit creates a force tending to release the armature. The releasing system is energized through a differential circuit at whose output the current is quite insignificant under normal conditions and also in the presence of swinging but attains the required value when a short circuit occurs.

Under normal conditions or in the event of a short circuit outside the protected zone there is a flow of current through the winding of the system because the direction of the resultant rectified current coincides with the unrestraining direction of the rectifier. When a short circuit occurs within the protected zone, the resultant current changes its sign, and the rectifier does not let it flow through the winding. As a result, the magnetic flow in the operating system and the retaining force are diminished to an insignificant value, and the armature is released closing the contacts.

There is practically no air gap in the magnetic circuit; therefore, the very small ampere-turns of the operating winding create a considerable retaining force. Owing to this the relay can also be used as a sensitive zero indicator.

The rectifier renders the relay sensitive to the polarity of the current. The large magnitude of the operating force permits a reliable contact system to be established fit directly to operate a switch. Thus, the functions of all the main protection elements are combined in this scheme — starting impulse, directional action, distance response, restraint for swinging and faults in the voltage circuits, closure of breaker disconnecting circuits. They are all combined in a single mechanical operation—the release of the relay armature. Thereby the problem of co-ordinating

the operations of various elements of a protective system is obviated and sensitivity, high speed of operation and reliability are secured. Practically, the time of action of this relay is equal to the duration of the transient state in the protection circuits.

When the relay with armature release which operates very quickly is used as the operating element of the protection scheme, we are faced with the problem of thoroughly smoothing out the rectified currents. Devices inserted for that purpose on the side of rectified current will possess inertia. On this consideration no special devices are provided for smoothing the current. The variable component of the rectified current is reduced by transforming the single-phase current previous to rectification into three-phase current whereupon the components are rectified and summed up.

A detective directional resistance relay arranged in accordance with the scheme just described will permit the minimum current at which the error of the relay will not exceed 10 per cent to be reduced to a value about 3 times lower than in the case of a directional resistance relay based on the four-pole induction type relay system (with equal consumption in the current and voltage circuits).

A schematic diagram of a detective distance relay with an elliptical characteristic is shown in Fig. 8, and its characteristic is shown in Fig. 12. Its torque is defined as

$$M = K\left\{\left|\dot{I}\dot{Z}_{p.s.}\right| - \left|\dot{U} - \frac{\dot{I}\dot{Z}_{p.s.}}{2}(1-\varepsilon)\right| - \left|\dot{U} - \frac{\dot{I}\dot{Z}_{p.s.}}{2}(1+\varepsilon)\right|\right\} \qquad (4)$$

where

$\dot{U}$ and $\dot{I}$ = short-circuit voltage and current;

$\dot{Z}_{p.s.}$ = impedance of the protected section up to the end of the zone;

ε = eccentricity of the elliptical characteristic.

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This relay is very similar in design to the directional resistance relay discussed previously. If $\varepsilon = 0$, the respective expressions for the torque become identical.

The only basic difference in the scheme of Fig. 8 as compared to Fig. 7, is that it involves an additional regulation of the eccentricity whereas the use of a polarized relay is not at all obligatory; an armature-release relay can be inserted instead on a similar scheme.

Important advantages are gained by the use of the relay with the elliptical characteristic since it can be made in-

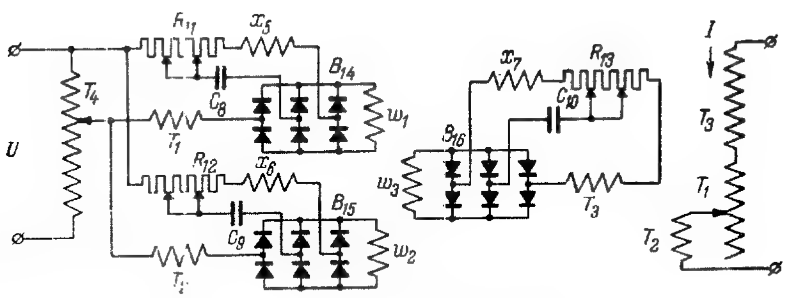


Fig. 8. Schematic diagram of a detective distance relay with an elliptical characteristic.

w_1, w_2 and w_3 — polarized relay windings; U and I — voltage and current applied to the circuit; T_1, T_2 and T_3 — transformers with air-gapped magnetic cores; T_4 — potential autotransformer; x_5, x_6 and x_7 — chokes; C_8, C_9 and C_{10} — condensers; R_{11}, R_{12} and R_{13} — added resistances; B_{14}, B_{15} and B_{16} — rectifiers.

operative for input resistances of the line under normal operational conditions and is a most expedient means of protection of long heavily loaded lines.

In the relay with an oval characteristic designed in the USSR in 1951 other non-linear elements instead of rectifiers are used, viz., the saturable transformers. Their characteristics are chosen to have secondary quantities expressed through primary ones as similar power functions:

$$U_2 = K_1 U_1^n \text{ and } I_2 = K_1 I_1^n . \tag{5}$$

With this condition satisfied and with secondary currents and voltages applied to the directional resistance relay circuit the relay characteristic in the complex R

and X plane is obtained in secondary quantities as a circle and in primary quantities as an oval (see Fig. 13).

By using saturable transformers we can obtain various types of resistance relays.

When a component proportional to the short-circuit current is added to the polarizing flux of an ordinary directional resistance relay, the characteristic is displaced in a certain direction as if it were transferred electrically along the line to compensate the voltage drop in the section corresponding to the zone of displacement. If the displacing voltage is supplied through a non-saturable transformer, the displacement of the characteristic has a constant value, independent of the current.

On the other hand, if the displacing voltage is supplied through a saturable transformer, the displacement is smaller the higher the current.

When the fault point is near the remote end of the line, the currents in the protected line decrease, hence the compensation increases. The characteristic circle slides along the line following the fault point. Such a relay with „sliding compensation" was developed in the USSR in 1950.

Other designs of a relay having a special characteristic are possible, but the use of non-linear elements of some kind is here an indispensable condition.

Modern distance protection equipment includes various auxiliary appliances intended to block the main operating devices, i. e., to render them inoperative for swings, for troubles in the voltage circuits, and so on.

Blocking appliances for swings were designed in the USSR in 1938 and have since been used with success in thousands of protective sets. The principle on which they are based is to bring the protective device in operation in response to a short-circuit fault for but a very short time interval sufficient for its intended action and to take it out of operation till the end of the short circuit or for a time overlapping the possible duration of the short-circuit fault conditions.

These appliances are started by means of a negative sequence current or voltage relays; in some individual cases they are started by means of a relay operating in response to the rate of change in current or voltage.

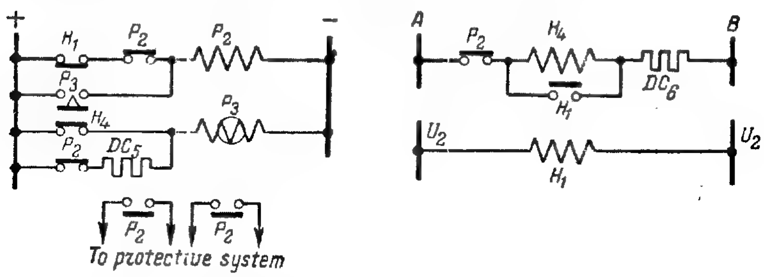


Fig. 9. Interlocking arrangement for power swings with immediate resetting after isolation of fault.

H_1 — negative sequence voltage relay; P_2 and P_3 — auxiliary relays; H_4 — voltage relay; DC_5 and DC_6 — added resistances.

With this method an operation of the protective device for swings is practically excluded. Figs. 9 and 10 show the wiring diagrams of two interlocking arrangements which differ from each other in the method of returning

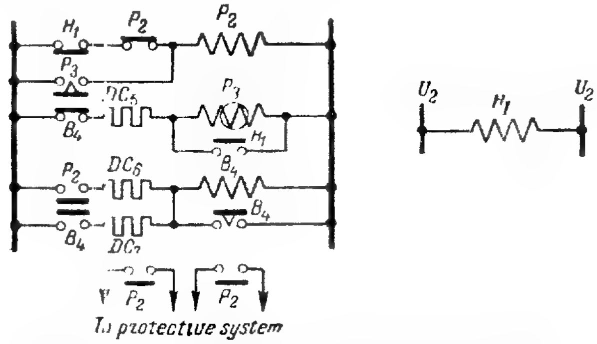


Fig. 10. Interlocking arrangement for power swings with fixed time resetting.

H_1 — negative sequence voltage relay; P_2 and P_3 — auxiliary relays; B_4 — time relay; DC_5, DC_6 and DC_7 — added resistances.

to the position where they are ready for operation again.

Interlock for swings is used in the relay practice of the USSR both for the first and second zones of distance protection. In the latter case the protective arrangement includes a relay that registers the fact of operation of the

distance-measuring element through the contacts of the blocking relay.

Interlock for troubles in the voltage circuits is obtained by relays locked in through filters of zero sequence voltage. In the presence of zero sequence current these relays come out of operation. One of such interlocking arrangements is shown in Fig. 11.

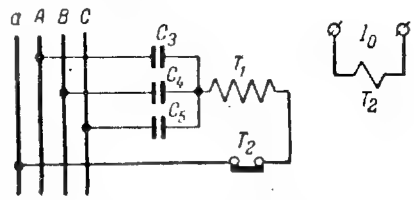


Fig. 11. Interlocking arrangement for faults in voltage circuits. T_1 and T_2 — current relays; C_3, C_4 and C_5 — condensers; I_0 — zero sequence current.

In the protection of long heavily loaded lines combined interlocks have been designed for swinging and for troubles in the voltage circuits; they are operated by a relay responding to the rate of current change. As sensitive elements of the blocking appliance electromagnetic a. c. relays or polarized relays energized through rectifiers are used.

As an example of distance protection, where several of the described appliances are used, we may indicate a three-step distance protection for networks of 110—220 kv with a large ground fault current. It includes starting elements constructed in accordance with the scheme in Fig. 5. The distance relaying includes two distance measuring elements. One is designed in accordance with the scheme in Fig. 5 and is intended to operate for symmetrical short circuits while the other is constructed in accordance with the scheme in Fig. 6 and is intended to operate for non-symmetrical short circuits.

This protection arrangement includes an interlock for swinging, which is actuated by a negative sequence voltage relay. According to the method of returning to normal position adopted in the protected network for similar arrangements, the device may be ready to repeat its

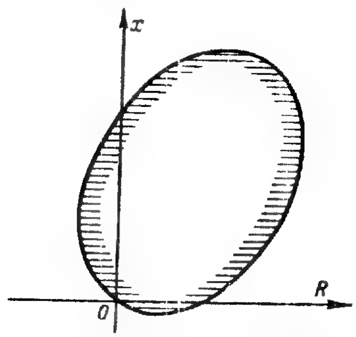


Fig. 12. Elliptical characteristic of resistance relay (operation zone of relay is shaded).

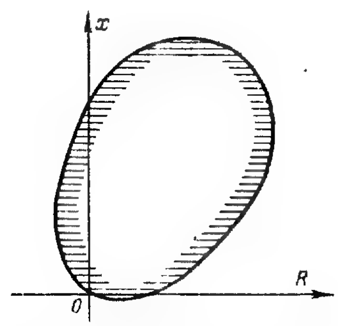


Fig. 13. Oval characteristic of resistance relay (operation zone of relay is shaded).

operation immediately after the short circuit is cleared, or after a fixed time interval.

The directional resistance relay is blocked in the first and second zones while the polyphase compensation relay is blocked in the first zone only.

The protection relaying has a range of setting of 0.25 — 20 ohms. The current at which a 10 per cent accuracy of operation is secured is 2 *A* for a setting of 0.75 ohm or more. The time of operation for faults within 75 per cent of the protected zone can de reduced to two periods (40 milliseconds).

II. CARRIER-CURRENT RELAYING

Two types of quickly operating carrier-current protective systems have been designed in the USSR and have come to extensive use on 110 — 220-kv lines: a directional type with carrier-current blocking and a phase-differential type. In both of them filters for symmetrical components are used making it possible to apply a small number of very simple relays combining the simplicity of design with a high sensitivity. For all kinds of fault currents they are highly sensitive both to non-symmetrical and symmetrical short circuits, yet they are inoperative for swings and overload.

For very long 400-kv transmission lines under construction new types of quickly operating carrier-current protective systems have been developed.

On transit transmission lines of 110 — 220 kv provided with three-phase automatic reclosing equipment both of the above-mentioned systems have been used. On lines with single-phase automatic reclosing the phase-differential protective system may be recommended, since it can remain in operation and protect the line when two phases are working whereas the directional type protective system with filters must automatically come out of operation in that case. Otherwise it will respond to two-phase operational conditions when voltage transformers are being connected to substation buses as if a fault occurred in the protected zone.

On lines having branch circuits for power take-off the directional protective system is mainly used because with this system it is easier to secure discrimination for external faults. An added relay equipment is installed on the branch circuit.

In both protective systems the same type of high-frequency receiver-transmitter is used. An extensive use of high-frequency channels on electric transmission lines for purposes of relay protection, telemetering and supervisory control makes it sometimes very difficult to choose the proper carrier frequency of the given channel so as to tune out from the receiver the interfering influence of the neighbouring high-frequency channels. Within recent years a new receiver-transmitter equipment has been designed in the USSR and extensively applied to the two systems of protection. It is provided with a quartz crystal control of the carrier frequency of the transmitter, which permits the use in the receiver of a frequency filter with a narrow pass-band whereby interference of different high-frequency channels is reduced considerably. This, in turn, affords the possibility to increase the number of high-frequency channels used simultaneously on electric transmission lines.

Fig. 14 represents a schematic diagram of the differential type protective system used on 110—220-kv lines and Fig. 15—a general view of the system's panel. For non-symmetrical short circuit the protective system is operated by relays responsive to symmetrical current components of negative and zero sequences. For symmetrical faults the system is operated by a distance relay coupled

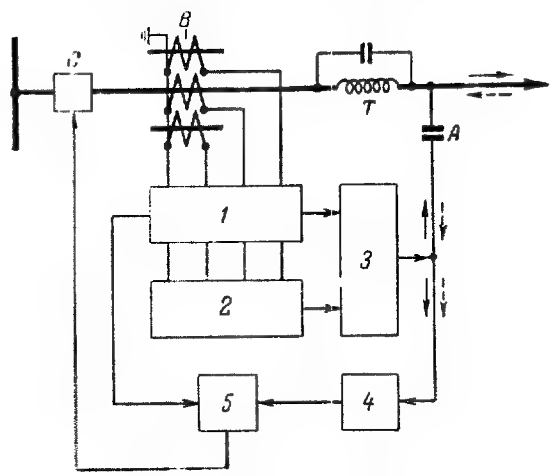


Fig. 14. Schematic diagram of the phase-differential carrier-current protective system for 110—220-kv lines.

1—starting element; *2*—manual control element of transmitter; *3*—transmitter; *4*—receiver; *5*—current phase comparing element; *A*—coupling condenser; *T*—line trap; *B*—current transformers; *C*—line circuit breaker.

with a device which instantaneously responds to the occurrence of a short circuit. For operation of this device it is enough to have a non-symmetrical fault lasting 0.002—0.004 sec. A restraining arrangement prevents the operation of the protective system in response to overloads on the line or to swings in the system.

In the phase-differential protective system high-frequency currents are used for comparing the phase angles of the currents at the ends of the protected line via combined filters of the $\dot{I}_1 + K_2\dot{I}_2$ type for symmetrical current

components of positive and negative sequences. The voltage at the output terminals of the filter is used for manual control of the high-frequency transmitter operating at half-period intervals on industrial frequency.

The filter of the $\dot{I}_1 + K_2\dot{I}_2$ type has several important advantages over the $\dot{I}_1 + K_0\dot{I}_0$ type which is likewise used in phase-differential protection. Above all, with the use of the $\dot{I}_1 + K_2\dot{I}_2$ type filter the behaviour of the phase-differential protective system is independent of the fault resistance in case of internal faults, and sensitive starting elements of reverse sequence current can be used both under two- and one-way feed conditions.

The use of the $\dot{I}_1 + K_2\dot{I}_2$ type filter required a special scheme because otherwise it would have been impossible to use it on account of:

(1) low sensitivity for symmetrical short circuits;

(2) lack of phase-angle constancy of the voltage across the high-frequency transmitter. This takes place when the current at the input of the filter changes and when a non-linear resistance (voltage stabilizer) is inserted at the filter output in order to limit the voltage for large short-circuit currents.

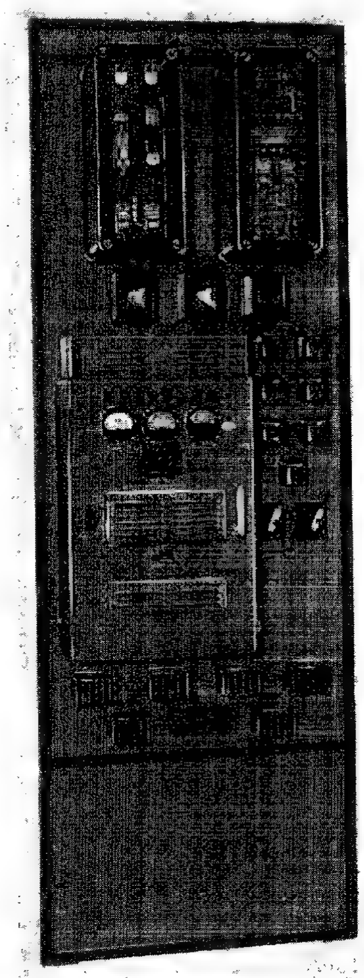


Fig. 15. Panel of phase-differential carrier-current relay for 110—220-kv lines.

However, this cannot be permitted on account of the operational conditions of the protective system in case of internal faults when the currents at the two ends of the line may considerably differ from each other.

The problem of application of $\dot{I}_1 + K_2\dot{I}_2$ type filter has been solved by inserting at the filter output a resistance and a capactiy, the values of which are obtained from the following expression:

$$Z_K \varepsilon^{j\varphi_K} = Z_H \varepsilon^{-j\varphi_H} \qquad (6)$$

where Z_K = total impedance of the filter measured on the output side with the primary circuit opened;

Z_H = resultant impedance of the filter output (capacity and resistance);

φ_K and φ_H = the angles of the respective impedances Z_K and Z_H.

When condition (6) is satisfied, voltage resonance takes place in the secondary circuit of the $\dot{I}_1 + K_2\dot{I}_2$ filter, which permits the protective system to be made most sensitive to every kind of short circuit. Moreover, the insertion of a resistance and a capacity secures a constancy of the voltage phase angle at the filter output when the current at the input is altered.

The phase characteristic of the phase-differential relay is shown in Fig. 16. In accordance with this curve the blocking angle is taken to be $\pm 45°$. From theoretical and experimental studies and from long experience in service it may be concluded that with this angle the protective system is reliably blocked for external faults. The operation of the phase-differential system for internal faults is shown by the oscillogram given in Fig. 17,*a* while its behaviour towards external faults is represented by the oscillogram in Fig. 17,*b*.

A general view of the panel of the directional filter type carrier-current equipment, as used in 110—220-kv

networks, is shown in Fig. 18. The starting element in this type of equipment is a relay responsive to negative

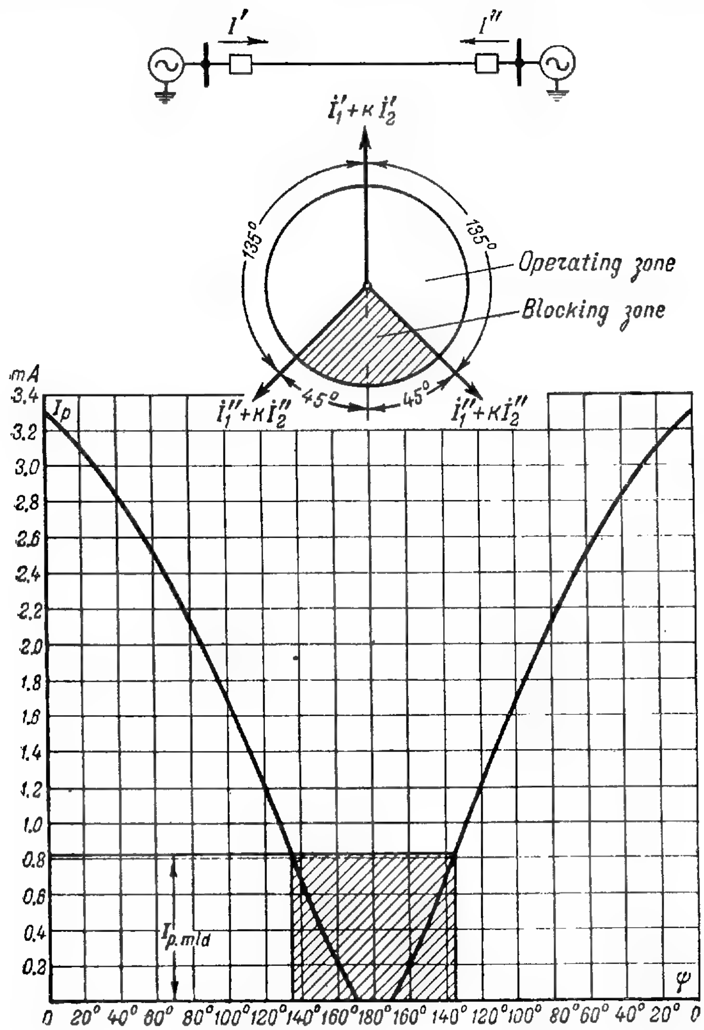
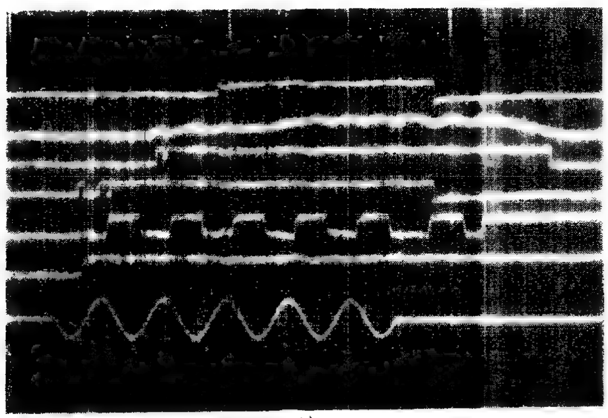


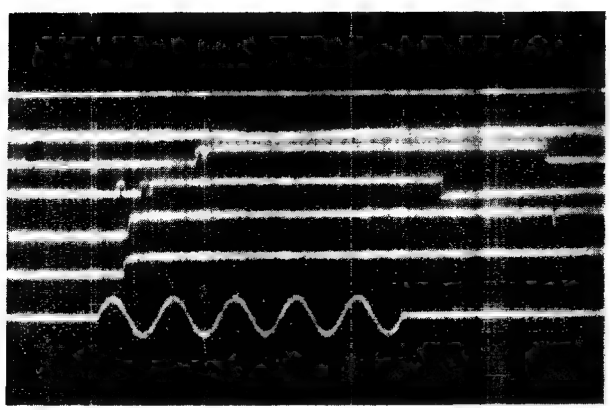
Fig. 16. Phase characteristic of phase-differential carrier-current relay for 110—220-kv lines.

sequence symmetrical components of voltage and current, which acts in combination with a device registering instantaneously the appearance of a short circuit. With the

starting element so designed it is possible to dispense with the use of separate starting relays for each phase and for the neutral. Besides, this starting relay exercises



a)



b)

Fig. 17. Operation oscillograms of phase-differential carrier-current relay.

a — internal fault; *b* — external fault; *1* — short-circuit current; *2* — contact of transmitter starting relay; *3* — current of receiver; *4* — contact of starting element in tripping circuit; *5* — contact of relay for connection of current-phase comparing element to receiver; *6* — current in relay of current-phase comparing element; *7* — current in tripping circuit.

the functions of an element determining the kind of fault (symmetrical or non-symmetrical) and blocking the protective system for swings.

An important feature of this directional filter type protective equipment is the remote controlled start of the transmitter at the other end of the line by carrier currents when the starting element comes into operation at one of the line ends. By means of a high-frequency return signal this arrangement prevents the protective equipment from inadvertent operation when the starting element at one of the line ends refuses to respond to an external fault or to ruptures in current and voltage circuits. The use of a remote controlled start for the transmitter has permitted an effective protection to be established with only one starting element for both the high-frequency and relay part of the protective equipment.

A schematic diagram of the remote controlled start of the transmitter by

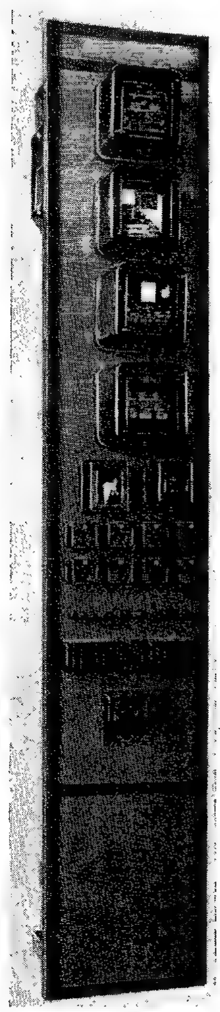


Fig. 18. Panel of directional filter type carrier-current protection for 110—220-kv lines.

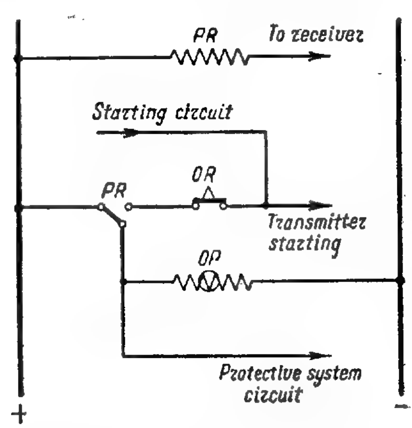


Fig. 19. Diagram of remote controlled start of transmitter by carrier currents in directional filter type protective equipment for 110—220-kv lines.

carrier currents is shown in Fig. 19. When the transmitter is started at one of the line ends, a polarized relay *PR* inserted in the anode circuit of the receiver comes into operation at the other end and also starts the transmitter.

The role of the directional element for power in this protective equipment is played by a relay which in the event of any kind of non-symmetrical fault responds to reverse sequence power and in case of symmetrical faults to direct sequence power.

Carrier-Current Relaying of 400-kv Lines

On account of the magnitude of power transmitted along 400-kv lines and because of their great lengths the requirements to be satisfied by the relay protection of these lines are very high indeed. The conditions for stability in parallel operation impose strict time limitations on the protective response to short circuits which on 400-kv lines should not exceed 0.02 — 0.04 sec. Contrary to the present day practice, the 400-kv lines under construction, in view of the responsible nature of their work, will be provided with two sets of high-speed carrier-current protective equipment designed on different principles. Each of them will reliably secure a stable operation of the system in the event of a short circuit. When the phase-differential and directional carrier-current protective systems are used in combination, the special advantages of either can be turned to full account.

Just as in the case of 110—220-kv lines, the carrier-current relaying of 400-kv lines involves the use of symmetrical component filters and is, therefore, inoperative for swings and overloads in the system. In working out the scheme single-phase automatic reclosing of lines was taken into consideration, and it was also reckoned that the line might go on for a long time with only two phases when the third one is in repair.

The large extension of 400-kv lines necessitates a more sensitive protective equipment compared with that used on 110—220-kv lines. Great lengths and the use of series

capacity compensation create specific conditions in a transient state caused by fault, which should be taken into account. Because of the presence of an aperiodic component in the short-circuit current containing no frequencies distinct from the main frequency of the industrial current special filters had to be provided in the protective systems of these lines for isolating the current and voltage of the main frequency.

Capacitive currents in 400-kv networks are sometimes comparable to short-circuit currents. So it was necessary to include in the protective system some devices for the compensation of capacitive currents, which would prevent the protective system from mal-operation for these currents on the occurrence of external faults. These devices are connected to that phase sequence voltage for which the system is operative. If they are inserted in each of the semi-sets of the system, their admittance is defined by the expression

$$Y_K = \frac{1 - \mathrm{ch}\,\gamma l}{Z_C\,\mathrm{sh}\,\gamma l} \qquad (7)$$

where

γ = coefficient of wave propagation;

Z_C = characteristic impedance of the line;

l = length of the line.

The capacitive current I_K thereby compensated in either semi-set is defined as

$$I_K = UY_K \qquad (8)$$

where U = voltage of the respective phase sequence.

The phase-differential protective equipment of 400-kv lines operates, as it does in 110—220-kv networks, for all kinds of short circuits, symmetrical or non-symmetrical. A new essential feature here, aside from the use of special frequency filters and capacitive-current compensation devices, is a starting element of a particular type, which operates for non-symmetrical short circuits. It is designed to meet the high requirements for sensitivity of the 400-kv

lines protection. The current I_p in the relay winding of the new starting element is defined as

$$I_p = f\,|\dot{U}_2 - \dot{I}_2 Z_{2K}| \cdot |\dot{I}_0 - \dot{U}_0 Y_{0K}| \qquad (9)$$

where

$\dot{U}_2$, $\dot{U}_0$, $\dot{I}_2$ and $\dot{I}_0$ = voltages and currents of reverse and zero sequences at the site of the equipment;

Z_{2K} and Y_{0K} = impedance and admittance of the compensation devices.

Owing to the compensation devices equal currents flow in the relay windings of the starting elements at both ends of the line in the event of an exetrnal fault, which is a prerequisite for selective operation of the phase-differential protective system. Admittance Y_{0K} is obtained from equation (7) by substituting the values of γ and Z_C corresponding to the zero sequence components. Impedance Z_{2K} of the compensation device blocking the starting element can be determined from the relation

$$Z_{2K} = Z_C \operatorname{th} \frac{\gamma l}{2} \qquad (10)$$

where γ and Z_C are to be assigned the values corresponding to the reverse sequence components.

Since two types of carrier-current relaying are contemplated on 400-kv lines, one of which operates for all kinds of fault, and the probability of symmetrical faults being small, the directional protective system with carrier-current blocking is designed to operate for non-symmetrical faults.

In this connection directional elements for negative and zero sequences are used that afford the possibility of a sensitive and simple construction of relay.

In order that two-phase working condition of the line should produce the same effect on the protective system as an external fault, feeding of the protection voltage circuits through voltage transformers connected to the line is contemplated. Directional protective systems with

carrier-current blocking having the above-mentioned qualities are made in two types of different construction.

In one of them the directional elements are power induction relays of two-sided operation with a cylindrical

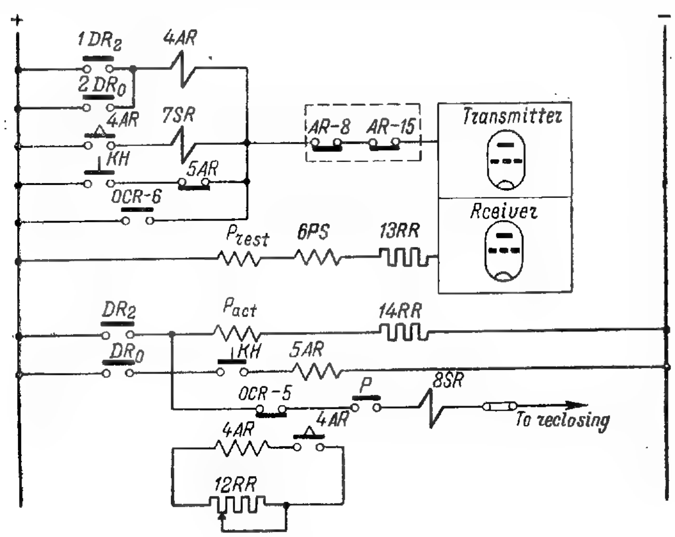


Fig. 20. Schematic diagram of directional protective equipment with carrier-current blocking involving an induction power relay of two-sided operation.

rotor. On either end of the line are installed a negative sequence and a zero sequence power relays. The electromagnetic torque at the power relay is defined by the equation

$$M = K_1 UI \sin\varphi - K_2 U^2 - M_m \qquad (11)$$

where

U and I = secondary phase voltage and current of respective sequence;

φ = displacement angle between U and I;

K_1 and K_2 = constants depending on the construction;

K_2U^2 = torque that compensates the action of capacitive currents of the line;

M_m = mechanical counter-torque.

A schematic diagram of this type of directional protective system is shown in Fig. 20. If the power sign

corresponds to that caused by an internal fault, the two power relays *DR*, or one of them, will act towards isolation of the fault setting the operating elements in motion through the contacts of the polarized relay *P*. If, on the contary, the power sign indicates an external fault, the power relays act towards starting the transmitter. The blocking signal is received by the checking winding of relay *P*. The transmitter is started for a longer time than the duration of an external fault (about 0.1 sec.); its delay is effected by means of relay 4*AR* which has a certain time lag in resetting. This is the way to prevent the protective device from maloperation for sharp deflections of the moving system in a transient state and for change in power sign. The power and time lags of the power relay are less when it acts towards starting the transmitter than towards the isolation of the internal fault.

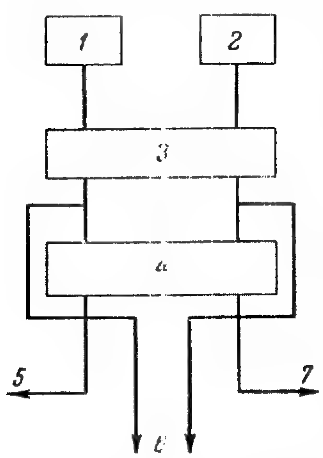


Fig. 21. Schematic diagram of directional protection with phase-responsive circuit.

1 — current filter; 2 — voltage filter; 3 — directional element with phase-responsive circuit; 4—operating element; 5 — reception of restraining signal; 6 — to restraining; 7 — to tripping.

In the other directional type protective system with carrier-current blocking (Fig. 21) the directing element is a phase angle responsive arrangement with semi-conductor rectifiers, which controls the power sign in the a. c. circuit. It is provided with a summarizing transformer having a three-leg core and with copper-oxide rectifiers.

The primary windings of the transformer, viz., the voltage windings on the two lateral legs and the current winding on the central leg, are supplied from the respective symmetric component filters. Its two secondary windings are connected through frequency filters to two rectifying bridges; these bridges are in connection with

a polarized relay responding to the difference of rectified currents and with the starting valve of the high-frequency transmitter responding to the difference of rectified voltages.

In one of the lateral legs of the transformer the magnetic fluxes created by E' and E'' of the primary windings

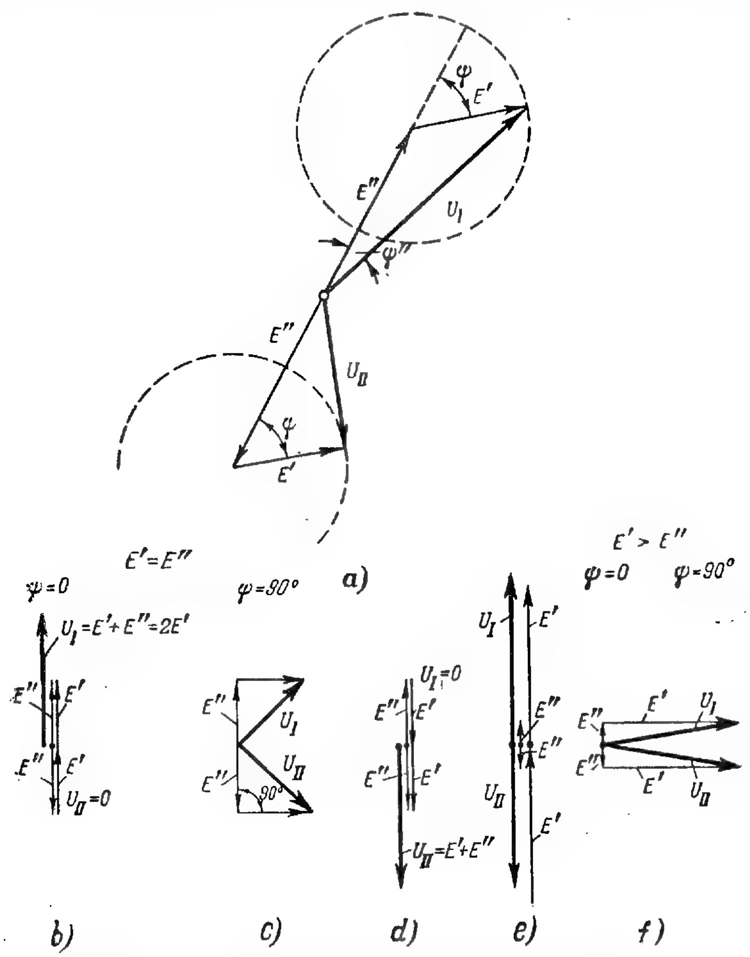


Fig. 22. Vector diagram of phase-responsive circuit.
a) general case: $\Psi \neq 0$; $E' \neq E'$; $\Delta U_{-} = U_{I} - U_{II}$; b) $E'' = E'$; $U_{I} = E' + E''$; $U_{II} = 0$; $\Delta U_{-} = E' + E'' - 2E''$; c) $U_{I} = U_{II}$; $\Delta U_{-} = 0$; d) $U_{I} = 0$; $U_{II} = E' + E'$; $\Delta U_{-} = -(E' + E'') = -2E'$; e) $\Delta U_{-} = (E' + E'') - (E' - E'') = 2E''$; f) $U_{I} = U_{II}$; $\Delta U_{-} = 0$.

are summed up geometrically while in the other their geometrical subtraction takes place. Accordingly, the voltage at the secondary winding of one of the lateral legs will be proportional to the geometrical sum of the fluxes, or of E' and E'', while at the secondary winding of the other it will be proportional to the geometrical difference of the fluxes. In the circuit of the rectifying bridges loaded with the difference between the rectified currents or voltages an algebraic subtraction of the secondary voltage moduli takes place (see vector diagram in Fig. 22).

The difference between the rectified voltages ΔU_{-} (or currents) changes in sign and value as a function of the displacement angle between the fluxes, or between E' and E'', according to the relation

$$\Delta U_{-} = U_{\text{I}} - U_{\text{II}} \approx E'' \cos \psi. \qquad (12)$$

Thus, the phase-responsive arrangement can be used directly as a directional element of cosine type.

In the protection system we are concerned with phase-responsive arrangements are used as directional elements for negative and zero sequences. The vectors E' and E'' which create the fluxes in the summarizing transformer are linked with the currents and voltages by the relation

$$\dot{E}' = K_1 \dot{U}; \; \dot{E}'' = K_2 (\dot{I} - \dot{I}_K) \qquad (13)$$

where

$\dot{U}$, $\dot{I}$ = phase voltage and phase current of respective sequence;

$\dot{I}_K$ = compensation current proportional to the capacitive conductivity of the line;

K_1, K_2 = constants depending on the construction of the protective arrangement.

The directional elements for negative and zero sequences must be of sine type. In the directional element for negative sequence a sine characteristic is obtained owing to the displacement angles of current and voltage vectors in the symmetric component filters and in the

primary winding of the transformer current circuit due to the presence of leakage fluxes. In the zero sequence directional element a sine characteristic is obtained by the use of a special scheme where the voltage vector turns through an angle of $\pi/2$. Thus in the phase-respon-

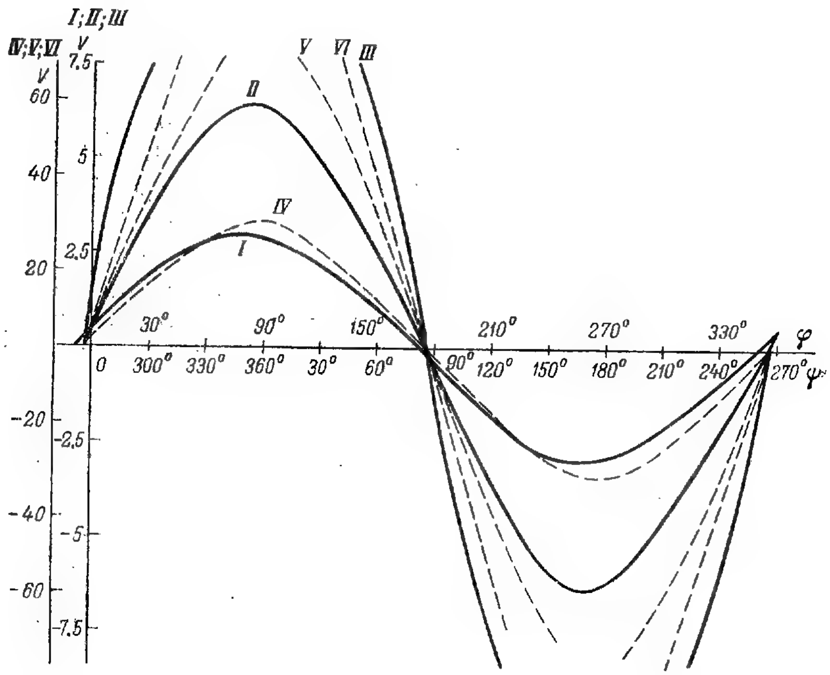


Fig. 23. Angular characteristics of directional high-speed carrier-current relaying with phase-responsive scheme.

	I	II	III	IV	V	VI
k_i	1	2	5	10	32	65
k_u	1	2	5	8	12	15

sive arrangement the relation $\Delta U_{-} = f(\varphi)$ for directional elements of negative and zero sequences is defined as:

$$\Delta U_{-} = 2K_2 (I - I_K) \sin\varphi \qquad (14)$$

where

φ = the displacement angle between current and voltage of respective sequence.

Fig. 23 represents $\Delta U_{-} = f(\varphi)$ curves obtained within a wide range of variation of short-circuit currents. From these curves it is obvious that the angular error of the directional element is small.

The phase-responsive arrangement of either directional element acts on a separate polarized relay which will isolate the faulty line if the output voltage corresponds in polarity to that of an internal fault. If, on the other hand, the polarity of the output voltage corresponds to that of an external fault, the two phase-responsive arrangements will start the high-frequency transmitter.

In the protective equipment the restraining signal is received by the circuit of a checking electromagnetic system which holds the moving system of the polarized relay in a position at which the contacts of the relay remain open.

Owing to the use of a contact-free start of the transmitter a quickly operating and reliable blocking of the protective system for external faults has become possible. This kind of start also secures a rapid re-orientation of the directional elements in various transient states or when the power changes its sign; this is most important for a high-speed protection of long 400-kv lines.

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ON IMPULSE DISCHARGE VOLTAGES ACROSS HIGH-VOLTAGE INSULATION AS RELATED TO THE SHAPE OF THE VOLTAGE WAVE

by

A. A. Akopian, V. P. Larionov and A. S. Torosian

The paper contains the results of an investigation of the spark discharge in 100—200-cm air gaps between a rod and a plane or between two rods used as electrodes with voltage waves of various shapes. On the basis of these results is proposed a method of constructing volt-time characteristics for various forms of impulse voltage wave. Some examples are given which show a good agreement between the curves thus obtained and the experiment data.

The insulation co-ordination in high-voltage systems is usually based on volt-time characteristics for a standard voltage wave (1.5/40 μsec, 1/50 μsec, and so on). In practice, however, the atmospheric overvoltage waves which may act on the insulation vary widely in form. Of the various waves the following should be considered in the first place: a) unipolar waves with a sharp decline (chopping) after the

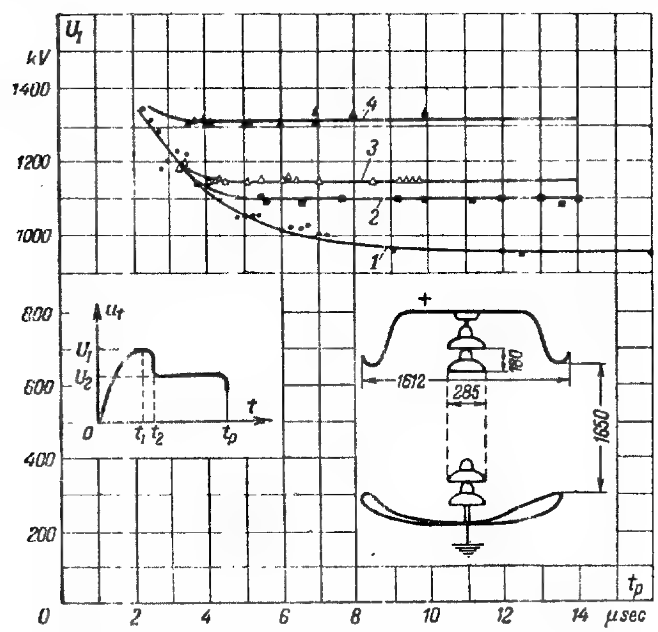

Fig. 1. Volt-time curves for a chain of 12 insulators of П-4.5 type with fittings (positive waves).

1 — standard wave 1.5/40 μsec; partly chopped waves; 2 — t_2=4.0—5.0 μsec; u_2/u_1=0.6—0.61; 3 — t_2=2.0—2.5 μsec; u_2/u_1=0.77—0.8; 4 — t_2=1.5—2 μsec; u_2/u_1=0.64—0.67.

amplitude is reached, which may arise in the insulation of an electric transmission line under a direct lightning stroke and also in remote small capacity parts of a substation; b) unipolar waves with a high-frequency oscillation component, which arise on the equipment of a substation of high input capacity.

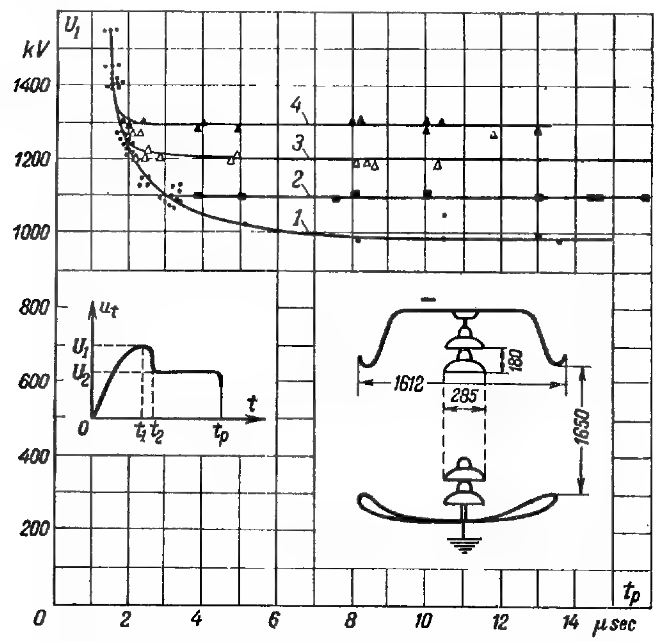

Fig. 2. Volt-time curves for a chain of 12 insulators of П-4.5 type with fittings (negative waves).
1 — standard wave 1.5/40 μsec; partly chopped waves; 2 — $t_2 = 3.0$—3.8 μsec; $u_2/u_1 = 0.7$; 3 — $t_2 = 1.8$—2.0 μsec; $u_2/u_1 = 0.78$; 4 — $t_2 = 1.2$—1.4 μsec; $u_2/u_1 = 0.66$—0.69.

The influence of the wave shape is represented graphically in Figs. 1 and 2; the volt-time curves in these figures refer to a chain of 12 insulators of П-4.5 type for unipolar waves of the standard shape and for waves dropping abruptly after the amplitude is reached (partly chopped waves). A considerable effect on the volt-time curve is produced by the time t_2 of the voltage drop and by the voltage value u_2 following the chopping. The minimum discharge voltage attains a value of

1,300 kV for partly chopped waves of positive polarity ($u_2/u_1 = 0.64 - 0.67$ and $t_2 = 1.5 - 2$ μ sec) and is merely 950 kV for standard waves (Fig. 1).

Taking account of the wave shape influence in surge voltage on the dielectric strength of the insulation is a matter of increasing importance because of the steady rise of the working voltage in modern high-voltage systems. A number of papers on this problem has been published [1—6], but no satisfactory method has been developed as yet to permit an adequate evaluation of the wave shape influence on the dielectric strength of the insulation.

EXPERIMENTAL SET-UP AND PROCEDURE

Subjected to the test were 100—200-*cm* air gaps, the electrodes being a rod and a plane or two rods. As a source of impulse voltage we used a generator of $\sim$ 3,500 *pF*, in some cases of $\sim$ 7,000 *pF*, in total capacity.

To obtain a complete picture of how the discharge develops the voltage between the electrodes within the gap investigated was oscillographed and simultaneously time base photographs of the discharge were taken, by means of which the instantaneous velocities of the leader phase development of the discharge could be determined. In measuring the voltage an ohmic potential divider of 15-kiloohm resistance was used. The discharge was photographed by a rapidly rotating camera of a drum type, in which the film moved at a speed of up to 200 *m/sec*; this was sufficient for determining the instantaneous velocities of the development of the leader when the total active resistance of the source circuit was about 2 kiloohms and the overvoltage was comparatively small. When the overvoltage was rather high (up to 1.4 times the minimum discharge voltage), the speed of film motion in the camera was insufficient for determining the instantaneous velocities of the leader at the end of its development. Yet in such cases as well the discharge photographs were fairly distinct, and the instantaneous velocities of the leader could be determined within 70—80% of the distance between the

electrodes, because at the end of the leader phase the voltage in the air gap dropped abruptly (chopping) so that the further development of the leader was checked, and the main discharge did not arise until later when its light could not affect the image of the leader on the photographic film.

THE RESULTS OF THE TESTS AND THE METHOD OF CALCULATION OF VOLT-TIME CURVES FOR AIR GAPS BETWEEN ROD-PLANE AND ROD-ROD ELECTRODES AND FOR VOLTAGE WAVES OF VARIOUS SHAPES

Most elaborate were the tests with rod-plane electrodes; the rod was located above the plane and was the positive electrode. In this case the development of the leader in the

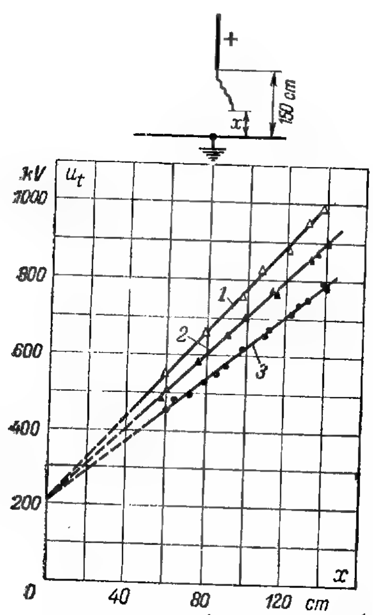

Fig. 3. Instantaneous voltage value u_t in relation to length x of gap portion yet unaffected by the leader; (positive rod)-plane electrodes spaced by an air gap $S = 150$ *cm*; voltage wave close to standard wave 1.5/40 μ sec.
1 — wave amplitude $u_1 = 990$ kV; 2 — $u_1 = 900$ kV; 3 — $u_1 = 790$ kV.

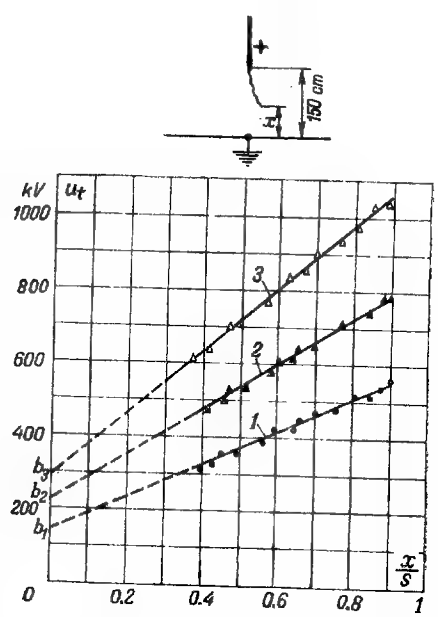

Fig. 4. Instantaneous voltage value u_t as a function of x for different gap lengths S between positive rod and plane.
$1 — S = 100$ *cm*; $2 — S = 150$ *cm*; $3 — S = 200$ *cm*.

gap starts only from the upper electrode, and the process is not complicated by leaders developing from below.

Oscillograms and time base photographs of the discharge development in the gap, with wave shapes very close to standard waves, were taken within a rather wide range of predischarge times from 4 μsec upwards. The data obtained for 100-, 150- and 200-*cm* air gaps reveal a linear dependence between the instantaneous value of the voltage applied to the electrodes u and the length x of that portion of the air gap which remained at the given instant undisturbed by the leader channel (Figs. 3 and 4). It is of interest to note that this linear relation rests invariable for different pre-discharge times. The distances b from the origin at which the straight lines cross the ordinate axis are directly proportional to the lengths of the air gaps tested. In kilovolts the numerical value of these intercepts is $b = 1.35\ S$ where S is the distance between the electrodes in centimetres. Each of the straight lines corresponds to voltage waves of equal amplitude. The angle formed by the straight line with the abscissa axis increases with increasing wave amplitude. It should be noted that in the rod-plane gap, on account of a steady increase of the pre-discharge current, the voltage wave is strongly distorted in the process of discharge formation, its front is reduced (Fig. 5), and at the time it has reached a maximum the leader bridges only 10—15% of the air gap length.

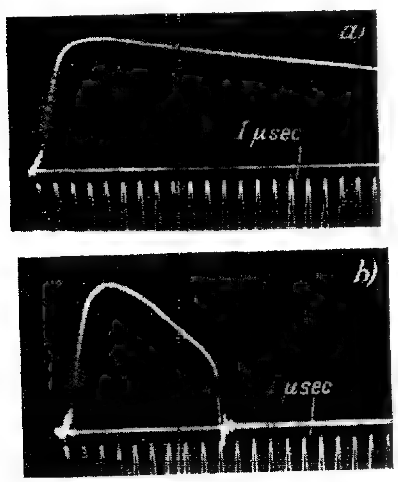

Fig. 5. Voltage wave distortion in the process of discharge formation between positive rod and plane electrodes spaced by an air gap $S = 200$ *cm*.

a — wave producing no discharge; *b* — wave distorted by the process of discharge formation.

Figs. 6 and 7 show the results of the tests with a 150-*cm* air gap between rod-and-plane electrodes under the action of unipolar partly chopped waves. For the instantaneous volt-

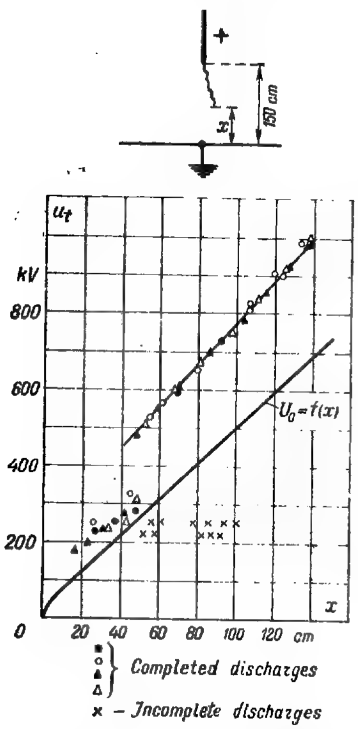

Fig. 6. Instantaneous voltage value u_t in relation to length x of gap portion unaffected by the leader for partly chopped waves with amplitude $u_1 = 1{,}000$ kV; (positive rod)-plane electrodes spaced by a distance $S = 150$ *cm*. $u_0 = f(x)$ is the voltage that will produce discharge at an interval x when applied for some length of time.

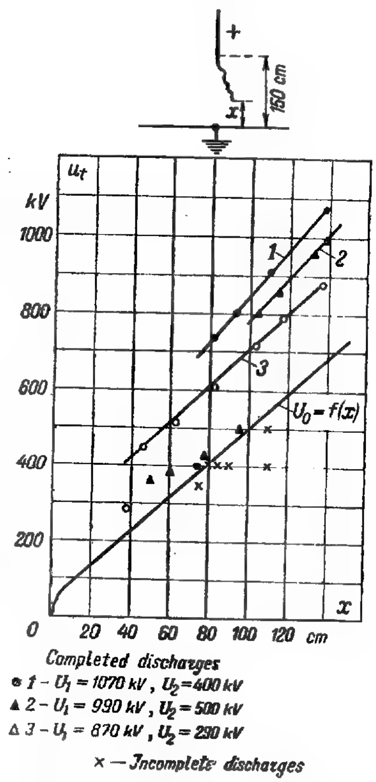

Fig. 7. Instantaneous voltage u_t as a function of length x for partly chopped waves; (positive rod)-plane electrodes spaced by $S = 150$ *cm*. $u_0 = f(x)$ is the voltage that will produce discharge at an interval x when applied for some length of time.

age values corresponding to that portion of the wave which preceeds the instant of partial chopping the above-stated linear relation between the instantaneous voltage value and the length x of the air gap portion not affected by the leader

is again valid. At the instant of partial chopping the rate of leader development is much reduced, and the discharge will not go on developing and come to completion unless the instantaneous voltage value after chopping, as measured for the entire interelectrode spacing, is higher than u_0 where u_0 is the voltage that will produce discharge when applied for some length of time (prolonged action) to the gap portion x yet unaffected by the leader.

In the figure points referring to the same completed discharge are marked by similar signs, and every incomplete discharge is shown by a single point marked with the sign $\times$ and corresponds to the length x at which the discharge stopped.

This condition for the completion of a discharge was observed also in the experiments with rod-rod air gaps. In this case the process of leader development starts from both electrodes. Therefore, x is here the distance between the heads of two leaders developing towards each other and u_0 is the discharge voltage under prolonged action for the length x.

Thus, for the discharge to develop further in the air gap the condition

$$u(t) \quad u_0(x)$$

is necessary at any given moment both in the case of rod-plane and in that of rod-rod electrodes.

In order to find out how the velocity of the leader development v, the instantaneous voltage value u_t and the length of the unaffected gap portion x are linked together it is well to consider the relations $v=f\,(u\;)$ for $x=$ const and $v=f\,(x)$ for $u_t-u_0=$const. In Fig. 8 are shown the relations $v=f\,(u_t)$ obtained with a 150-*cm* gap between a positive rod and a plane, the total resistance of the source circuit R being about 2 kiloohms. For constant values of x the relations between the instantaneous velocity of the leader and the applied voltage are straight lines which intersect the abscissa axis at points corresponding to values that are somewhat higher than the discharge voltage u_0 at the gap portion x. The angles at

which the straight lines are inclined to the abscissa axis become larger with diminishing x. This shows that v

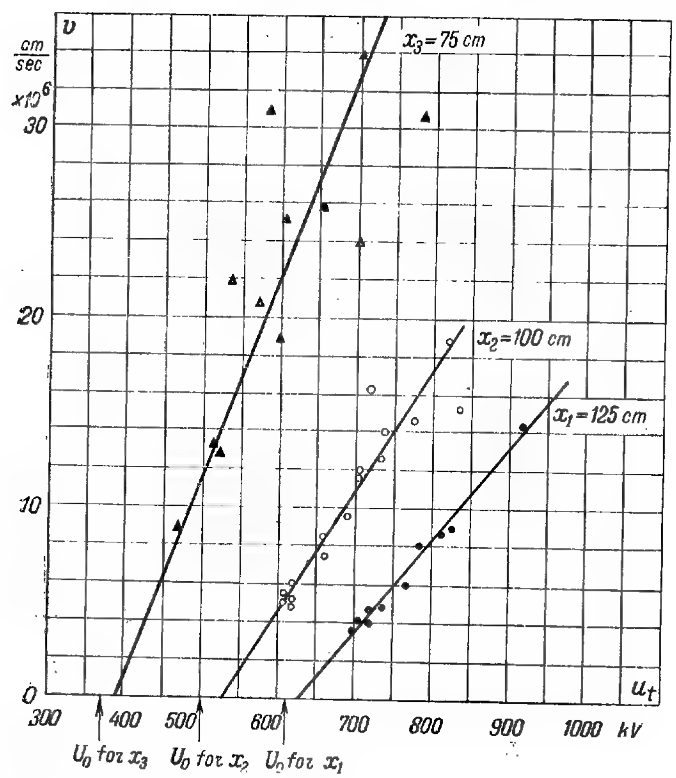

Fig. 8. Velocity of leader development v as a function of voltage u_t for $x=\text{const}$; (positive rod)-plane electrodes spaced by $S=150$ *cm*. Source circuit resistance $R\approx 2$ kiloohms. u_0 — voltage that will produce discharge when applied for some length of time.

must depend upon x as well. Approximately the equation of these lines may be written in the form

$$v \approx m_x (u_t - u_0) \tag{1}$$

where $m_x = k \cdot f(x)$ is constant for a given x.

The relation $v = f(x)$ for $u_t - u_0 = \text{const}$ represented graphically in Fig. 9 has been plotted point by point for two discharges, the points corresponding to values for which

$u_t - u_0 = \text{const}$. This relation is in accord with the data of Fig. 8 and can be expressed approximately by the equation

$$v \approx n_{\Delta u} \frac{1}{x - 0.23\,S} \tag{2}$$

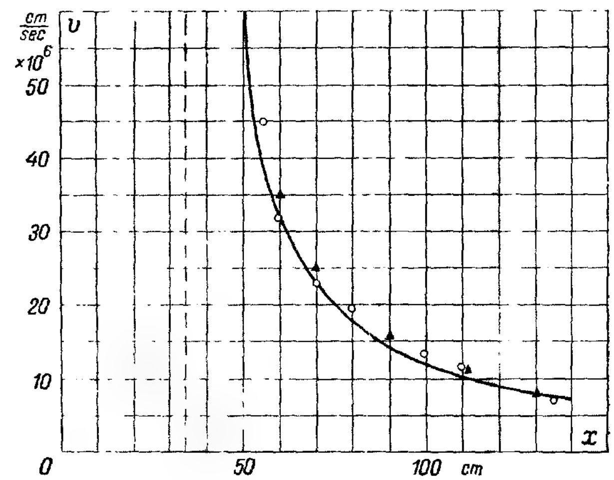

Fig. 9. Velocity of leader development v in relation to length x of gap portion unaffected by the leader for $u_t - u_0 = \text{const}$. Equation of the curve $v = \frac{800}{x - 0.23\,S}$, $S = 150$ cm. The points refer to two discharges effected between (positive rod)-plane electrodes; $u_t - u_0 = \Delta u = 200$ kV. Source circuit resistance $R \approx 2$ kiloohms.

where S is the full length of the interelectrode spacing and $n_{\Delta u} = k \cdot f(\Delta u)$ is constant for $\Delta u = u_t - u_0 = \text{const}$.

From equations (1) and (2) we have

$$v = k \frac{u_t - u_0}{x - 0.23\,S} \tag{3}$$

where the coefficient k can be expressed as

$$k = \frac{m_x}{f(x)} = m_x (x - 0.23\,S), \tag{4}$$

and its average numerical value, as determined from any of the straight lines of Fig. 8, is $k = 4$. The same value of k is

obtained when the length of the air gap between the rod and the plane is 100 or 200 *cm.* It should be noted that the value of k varies with the total resistance R of the source circuit. With the usual damping arrangement of the impulse voltage generator when the circuit resistance of the generator is not above 1,000 ohms, the mean value of k is about 9. For individual discharges the coefficient k may diverge from its mean value within $\pm 20\%$.

It may be remarked that in determining the coefficient k for overvoltages as high as 1.4 times the minimum discharge voltage the equations of the straight lines given in Figs. 3 and 4 can also be used:

$$u_t = b + ax = b + a(S - l) \tag{5}$$

whence

$$\frac{dl}{dt} = v = -\frac{1}{a}\frac{du_t}{dt} \tag{6}$$

where the value of the coefficient a can be determined from the data of Figs. 3 and 4 if the voltage wave amplitude is given. The derivative $\frac{du_t}{dt}$ is determined for some value of u_t from the voltage oscillogram, and then the corresponding values of v and x are calculated with the aid of formulas (5) and (6). When the values of v, u_t and $u_0(x)$ are given, the value of m_x is determined by means of formula (1) whereupon the coefficient k sought for can be found from formula (4).

As may be seen from equation (3), the velocity of the leader grows in the course of development and attains immense values when the head of the leader is as far away as $x_1 = 0.23\ S$. Therefore, that fraction of the interval x_1 has practically no effect on the pre-discharge time.

When the shape of the voltage wave is known as well as the relation $u_0 = f(x)$ for the given type of interval, the pre-discharge time can easily be determined by means of formula (3). Fig. 10 shows the method of determining the pre-discharge time for a 150-*cm* air gap between (positive rod)-plane electrodes. The voltage wave is divided with respect

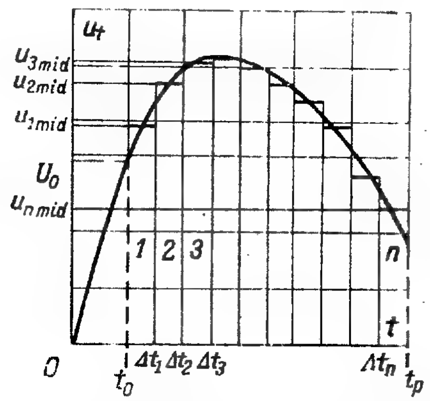

Fig. 10. Calculation of time of discharge between (positive rod)-plane electrodes by formula $v = k\dfrac{u(t) - u_0(x)}{x - 0.23\,S}$.

Time of delay $\tau = \sum_1^n \Delta t$; time of discharge $t_p = \tau + t_0$.

No.of interval	$u_{t\,mid}$	x*	$U_0(x)$	v	Δt	Δl	l
	kv	cm	kv	$\frac{cm}{\mu\,sec}$	μ sec	cm	cm
1	$U_{1\,mid}$	l	$U_0(l)$	v_1	Δt_1	Δl_1	Δl_1
2	$U_{2\,mid}$	$l - \Delta l_1$	$U_0(l - \Delta l_1)$	v_2	Δt_2	Δl_2	$\Delta l_1 + \Delta l_2$
3	$U_{3\,mid}$	$l - \Delta l_1 - \Delta l_2$	$U_0(l - \Delta l_1 - \Delta l_2)$	v_3	Δt_3	Δl_3	$\Delta l_1 + \Delta l_2 + \Delta l_3$
—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—
n	U_n	$l - \sum_1^{n-1} \Delta l$	$U_0\left(l - \sum_1^{n-1} \Delta l\right)$	v_n	Δt_n	Δl_n	$\sum_1^n \Delta l$
					$\sum_1^n \Delta t$		$\sum_1^n \Delta l \quad l - 0.23\,S$

* To simplify calculations values $x = l - \sum_1^{n-1} \Delta l$ at the start of the time interval were taken.

to time into equal intervals Δt, as small as possible, starting from the instant t_0 at which the instantaneous value of the wave voltage is equal to u_0 for the whole gap. By the

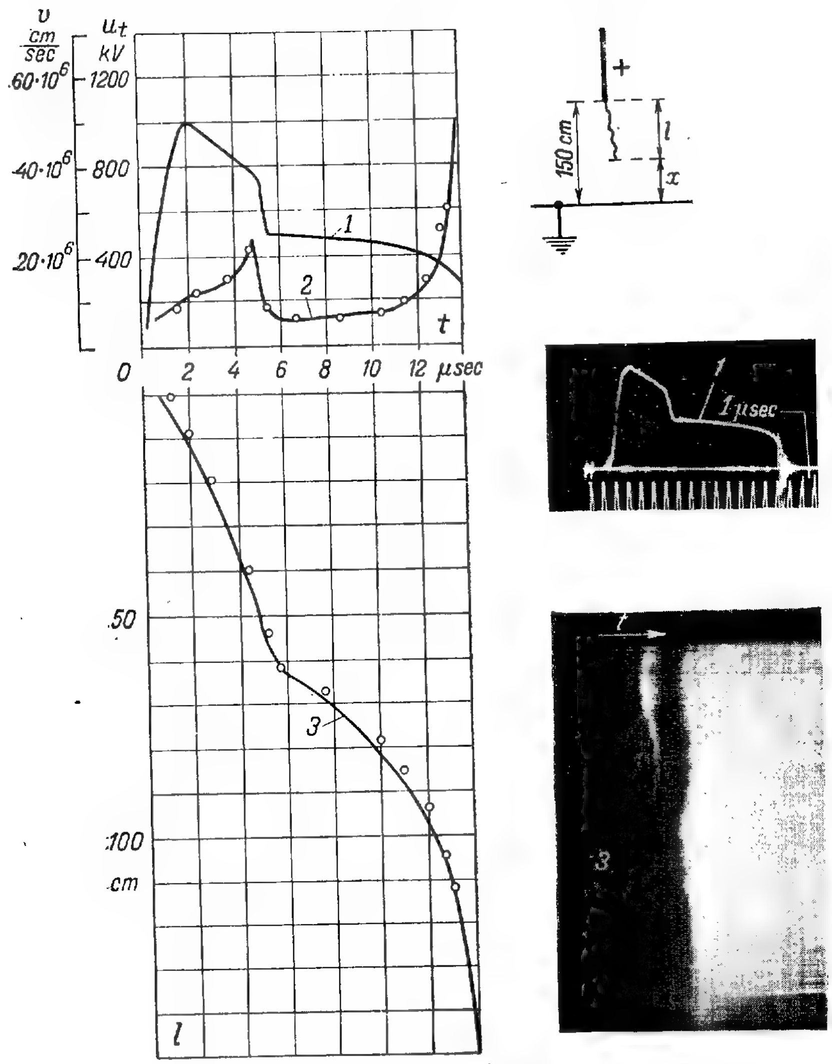

Fig. 11. Discharge with partly chopped voltage wave.
Continuous lines (experiment): *1* — voltage at the gap; *2* — leader velocity; *3* — discharge photographs.
The points were plotted by means of formula (3) for $k = 4.6$.

method of successive intervals (step by step) we can then find the time during which the head of the leader moves through a distance 0.77 S where S is the interelectrode spacing. This time represents the delay of the discharge.

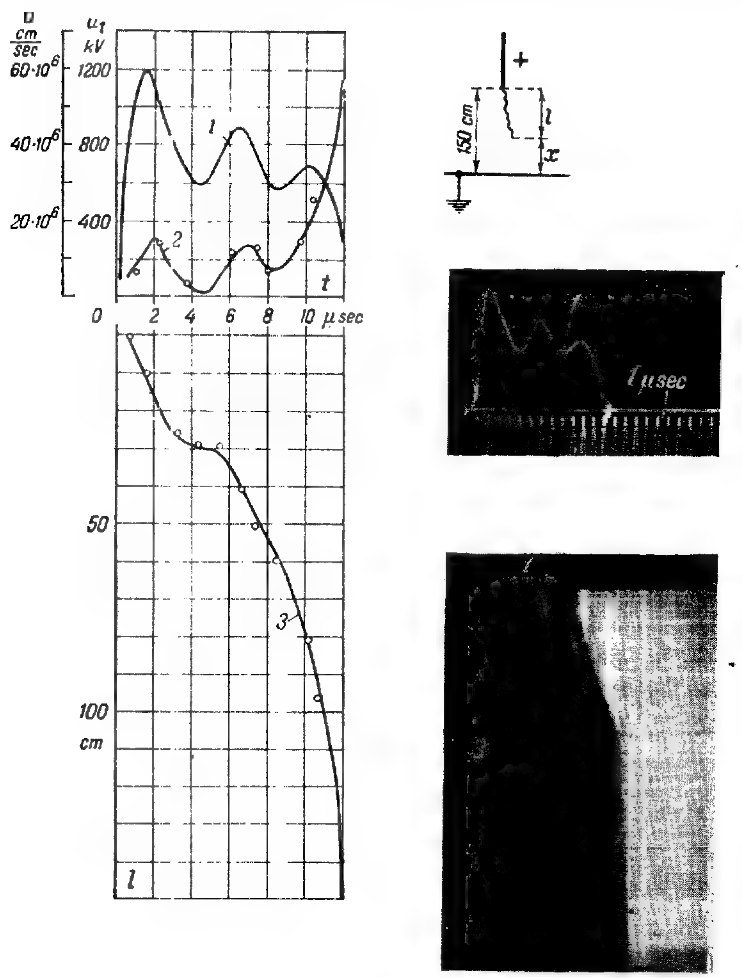

Fig. 12. Discharge with high-frequency oscillations superimposed upon voltage wave.
Continuous lines (experiment): 1 — voltage at the gap; 2 — leader velocity; 3 — discharge photographs.
The points were plotted by means of formula (3) for $k=3.3$.

That formula (3) can also be used in the case of waves widely different from the standard shape is shown by Figs. 11 and 12 in which experiment data (voltage oscillograms, discharge photographs) and points obtained by calculation are given.

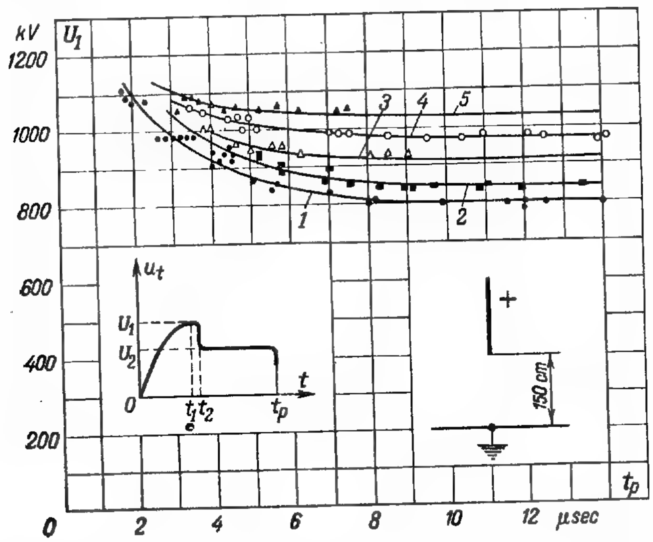

Fig. 13. Volt-time characteristics of the air gap between (positive rod)-plane electrodes; length of gap $S=150$ *cm*. Points are experiment data.

Continuous lines — calculations by formula (3) for $k=9$. 1 — standard wave $1.5/40\mu sec$ ($t_1 \approx 2$ μsec); partly chopped waves; 2 — $t_2=2$ μsec; $u_2/u_1=0.8$; 3 — $t_2=3$ μsec; $u_2/u_1=0.62$; 4 — $t_2=1.9$ μsec; $u_2/u_1=0.65$; 5 — $t_2=1.4$ μsec; $u_2/u_1=0.65$.

Fig. 13 shows volt-time curves referring to a 150-*cm* gap between (positive rod)-plane electrodes obtained by calculation for standard shape waves and for partly chopped waves (continuous lines). Points obtained by experiment are shown too. The good agreement between computed and experiment data in Figs. 11—13 is evidence of the applicability of formula (3) within a wide range of wave shape variations when plotting volt-time curves for a given gap between (positive rod)-plane electrodes.

In the case of rod-rod electrodes separated by a distance $S = 125$ *cm* the total rate of development of the discharge (which develops in this case from both electrodes) can be expressed approximately by the equation

$$v = 11 \frac{u_t - u_0}{x} \qquad (7)$$

which has been derived from experiment data for a total resistance of the source circuit not higher than 1,000 ohms.

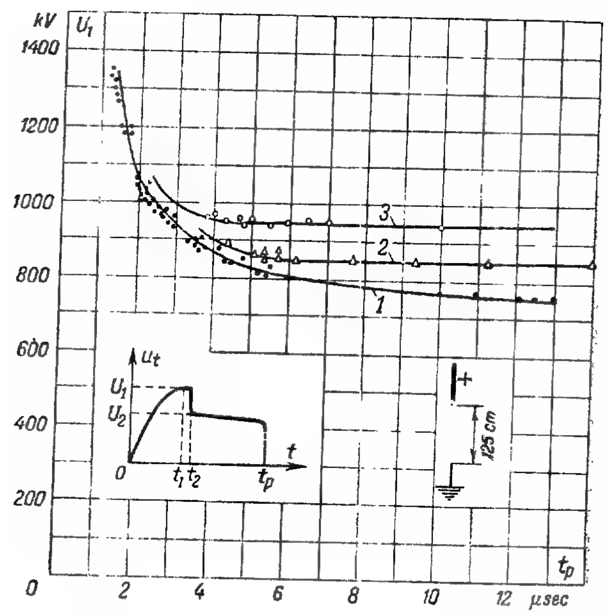

Fig. 14. Volt-time characteristics of air gap between rod-rod electrodes spaced by a distance $S = 125$ *cm* for positive polarity of the high-voltage electrode. Continuous lines have been plotted by means of formula (7). *1* — standard wave 1.5/40 μsec ($t_1 \approx 2$ μsec); partly chopped waves; *2* — $t_2 = 2.9$ μsec; $u_2/u_1 = 0.6$; *3* — $t_2 = 1.8$ μsec; $u_2/u_1 = 0.63$. Points indicate experiment data.

Fig. 14 represents volt-time curves obtained by means of formula (7). The experiment data are indicated by points.

CONCLUSIONS

1. The basic condition for the spark discharge to develop in the air gap between (positive rod)-plane or rod-rod electrodes is that at any fixed instant the instantaneous value of the wave voltage must be higher than the voltage u_0 that will produce a discharge when applied for some length of time to the gap portion yet unaffected by the leader channel.

2. At any given moment there is a univalued relation between the velocity of the leader development, the voltage applied to the gap and the length of the yet unaffected gap portion. In the case of rod-plane electrodes this relation can be written as follows:

$$v = k\frac{u(t) - u_0(x)}{x - 0.23\,S}.$$

By means of this equation volt-time curves can be plotted for voltage waves of various shapes. They will be found to agree well with experiment data.

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CONNECTING SYNCHRONOUS MACHINES IN PARALLEL BY THE SELF-SYNCHRONIZING METHOD

by

L. G. Mamikoniants

Automatic control of hydroelectric and steam-power generators and synchronous condensers can be largely simplified by using the self-synchronizing method for connecting them in parallel. The self-synchronizing method does not require preliminary matching of voltage and phase angle in addition to speed matching, yet it is a quick and reliable method for most synchronous machines.

The self-synchronizing method is used in the USSR for connecting in parallel generators and synchronous condensers with induction motors up to 90,000-kva rating.

INTRODUCTION

The method of precise synchronization generally used in connecting synchronous generators in parallel suffers from a number of serious drawbacks. Its main disadvantages are as follows:

a) The necessity of preliminary matching of the generator voltage with the line voltage in respect to magnitude, frequency and phase.

b) The delay in the process of synchronization as much as up to tens of minutes, particularly in cases of unsatisfactory speed control of prime movers or during system disturbances followed by line voltage changes in frequency and magnitude, when a quick connection of the generator to the line is a matter of especial importance.

c) The possibility of the generator being damaged when it is improperly connected in parallel with a large phase angle difference; such faults are known to occur in service now and again.

These disadvantages are encountered both on manual operation and with automatic synchronizers. The latter are complex devices as regards arrangement and design, and what is more, they are not reliable in operation when there are frequency and voltage swings in the system. In such cases while using automatic synchronizers it becomes necessary to recur to manual operation as well.

The use of various kinds of locking relays against a faulty connection to the line and of automatic synchronizers does not prevent possible damage to the machine. Indeed, experience shows that cases of synchro-

nization with a large phase-angle difference were not always the fault of men responsible for this operation; sometimes they were due to faults in the circuits through which the synchronizers and the locking devices were connected to the generator and line voltage transformers and sometimes to a delay in the operation of circuit breakers due to freezing.

The problem brought up within post-war years in the USSR, especially in connection with extensive plans for the introduction of a thorough automatic control on power stations, has been to work out a simple and reliable means of connecting generators in parallel.

As a result of investigations led preference has been given to the self-synchronizing method which is also known by the name of rough synchronization. This method is not new in principle but has been unduly neglected in practice.

Its essentials are as follows: the synchronous machine is brought up by the prime mover to a nearly synchronous speed (within a few per cent) and is connected to the system in an unexcited state. After that the machine is excited and synchronizes spontaneously.

The advantages of this method, as compared to precise synchronization, are as follows:

a) The method is simple and practically excludes the possibility of faulty connections to the system.

b) The connection is effected quickly, which is particularly important when system disturbances are to be removed.

c) The process of connection can be easily automatized.

d) The generator can be connected to the line even if the magnitude and frequency of the line voltage are subject to sharp changes or swings.

e) The connection of generators in parallel is simple even in those cases when the speed of prime movers is not controlled automatically and when remote operated switches for connecting generators are absent.

f) The connection between the system and the power station through a transmission line, if disturbed, can be restored swiftly by automatic reclosing of the line whereafter the generators of the station (all at a time or in sequence) are brought to in-step operation by the self-synchronizing method. This automatic reclosing with self-synchronizing is designated, for brevity, by the letters ARS.

On the other hand, the self-synchronizing method has some disadvantages, namely:

a) There is always a rush of current at the instant when the non-excited synchronous machine is connected to the line.

b) There is a brief voltage drop on the line at the instant when the generator is connected to it.

It is probably owing to the overestimation of the danger of these phenomena that the self-synchronizing method has not come to extensive use up to the present.

From some literary data[1] it appears that this method has been applied seldom and only to rather small generators (with no higher power output than 5,000 kw) having amortisseur windings, the power of the generator to be connected in parallel being at least 5 times as low as the total power of the generators operating on the line.

Some German authors have recommended the use of current-limiting reactors shunted after the generator has come to synchronism[2,3]. But the primary circuit is thereby greatly complicated which accounts for the limited application of this arrangement.

In view of the obvious advantages of self-synchronizing over precise synchronizing it seemed advisable to enter into a more elaborate analysis of the processes that take place in the generator and in the system when self-synchronizing is applied. As a result of these studies and a long-year experience of successful application of asynchronous starting for a large number of both asynchronous and synchronous machines (motors as well as synchronous concensers) with a power output of up to sev-

eral tens of thousands of kilovoltamperes in a unit, it is possible to decide the question we are concerned with in favour of the self-synchronizing method for various types of generators and synchronous condensers. Only a limited number of machines remain outside of the range of application of this method.

RUSH CURRENTS AT SELF-SYNCHRONIZING

At the first moment, when an unexcited synchronous machine is connected to a system, free currents arise in the rotor* and in the stator circuits. Owing to them the current that flows for some time along the stator winding exceeds several times the rated current; however, on account of some external resistance of the system (transformer, transmission line, and so on) this current, as a rule, is essentially lower in value than that due to a sudden three-phase short circuit whose action is allowed for in the design of any machine.

Thus, when a steam turbine-driven generator linked with a power transformer (generator-transformer bank) is connected to a line by the self-synchronizing method, the current will be 1.5—2.0 times less than the short-circuit current. The mechanical forces acting on the stator winding will diminish directly as the square of the current value, i. e., 2.25—4.0 times.

Currents close in value to those due to sudden three-phase short circuit arise when a generator is directly connected to a high-power bus. As a matter of fact, these conditions in a system usually take place only with generators of a relatively low power comparable in capacity to synchronous or induction motors which when started from full voltage are not damaged by currents equal in magnitude to those arising at self-synchronizing but acting for a far longer interval of time. Thus, the dura-

* The generator field winding must be connected in parallel with a field discharge resistance or the armature of an unexcited exciter in order that the field winding insulation should not break down from overvoltage at the instant of connection to the system.

tion of running up of big motors is often above 10—15 seconds whereas at self-synchronizing the current is reduced to its rated value within 1—2 seconds[4, 5, 6].

It should be noted that under otherwise equal external conditions higher mechanical forces arise in cylindrical rotor synchronous machines (steam turbine-generators) than in salient-pole synchronous machines (hydroelectric generators, synchronous condensers, etc.) because the pole pitch and the end-connection length of the stator winding are greater in the former than in the latter while the reactances which determine the initial value of the current are essentially smaller.

These circumstances have been taken into account in defining the field of application for the self-synchronizing method.

It is well to note that the maximum value the current may possibly reach at self-synchronizing is practically independent of the slip at which the machine is connected to the line. Therefore, even if the generator is unduly connected with a large slip, this will merely lead to an increase in the duration of enhanced currents which are not liable to damage the generator.

For the sake of comparison it may be remarked that the currents arising when an excited machine is asynchronously connected to the line may exceed 2 times those due to a sudden three-phase short circuit. Accordingly, the mechanical forces in the end parts will be 4 times greater in this case; that accounts for damages often caused to generators faultily connected in the excited state to the line, as has been stated previously.

TORQUE ACTING AT SELF-SYNCHRONIZING

The expression for the electromagnetic torque acting when a non-excited machine is being connected in parallel can be written in the general form as follows*:

$$m = m_{\infty} + \sum m_{fr} \qquad (1)$$

* A developed expression for the torque, which is rather cumbersome, is here omitted.

where m_{∞} = the torque in the steady state (asynchronous state in the general case);

m_{fr} = the damped free components of the torque due to interaction between the free components of the stator and rotor magnetic fields and between these and the steady state compulsory fields.

In machines with amortisseur windings and working with constant slip the torque in the steady asynchronous state can be expressed in the form

$$m_{\infty}=\frac{u^2}{2}\left\{\frac{x_d-x_q}{x_d x_q}\sin 2(\delta_0-st)-\frac{x_d-x_d'}{x_d x_d'}\times\right.$$
$$\times\frac{sT_d'}{1+(sT_d')^2}\left[1+\sqrt{1+(sT_d')^2}\sin\left(2\delta_0-\right.\right.$$
$$\left.\left.-\operatorname{arctg}\frac{1}{sT_d'}-2st\right)\right]-\frac{x_d'-x_d''}{x_d' x_d''}\cdot\frac{sT_d''}{1+(sT_d'')^2}\times$$
$$\times\left[1+\sqrt{1+(sT_d'')^2}\sin\left(2\delta_0-\operatorname{arctg}\frac{1}{sT_d''}-\right.\right.$$
$$\left.\left.-2st\right)\right]-\frac{x_q-x_q''}{x_q x_q''}\cdot\frac{sT_q''}{1+(sT_q'')^2}\times$$
$$\left.\times\left[1-\sqrt{1+(sT_q'')^2}\sin\left(2\delta_0-\operatorname{arctg}\frac{1}{sT_q''}-2st\right)\right]\right\} \quad (2)$$

where u = line voltage applied to the stator circuit;

δ = angle between the line voltage and the electromotive force of the generator;

x_d and x_q = direct and quadrature axis synchronous reactances respectively;

x_d' = direct axis transient reactance;

x_d'' and x_q'' = direct and quadrature axis subtransient reactances respectively;

T_d' = direct axis transient short-circuit time constant;

T_d'' and T_q'' = direct and quadrature axis subtransient short-circuit time constants respectively;

s = slip taken to be positive in the motor case;

m = electromagnetic torque taken to be positive in the generator case.

All reactances and time constants for a closed stator circuit are to be taken considering external resistances.

As may be seen from formula (2), the steady state torque is composed of constant components and of alternating sign components varying with the double slip-frequency.

The constant torque components determine the so-called average asynchronous torque which plays an important role in the pulling of the generator into synchronism. This component of the torque becomes zero at synchronous speed ($s=0$).

The variable sign components of the steady state torque do not essentially affect the process of pulling into step except in the neighbourhood of synchronous speed (at $s=1.0$ per cent and less). With slips larger than that the work due to this component approximates zero.

At synchronous speed ($s=0$) this component turns into reactive torque which has the familiar expression:

$$m_p = u^2 \frac{x_d - x_q}{2x_d x_q} \sin 2\delta_0. \qquad (3)$$

Owing to this torque salient-pole machines synchronize without excitation.

Experience shows that in the absence of surplus torque created by the prime mover cylindrical rotor machines can as well synchronize without excitation on account of a small reactive torque due to the presence of the large tooth and a small torque due to residual magnetization of the rotor.

Among the damped torque components due to free currents in the rotor and stator circuits only one is aperiodic, and it is damped very quickly (with a time constant $T_a/2$ where T_a is the short-circuit time constant of the stator winding). This component, as calculations show, is of small absolute magnitude and therefore practically has no effect on the synchronization. The other damped components may attain rather large absolute values, yet because of sign alteration they also have no appreciable effect on the synchronization process.

So the full expression of the torque can be of interest only in estimating the mechanical influences exerted on the generator itself immediately after it is connected to the line.

A study of the torques that act on the machine during the first period following its connection to the line may be done qualitatively assuming that the rotor circuits are super conductors. Then the electromagnetic torque can be expressed by a simple formula:

$$m = u^2\left(\frac{1}{x_d''} - \frac{1}{x_q''}\right)\Big\{\varepsilon^{-t/T_a}\sin\left[2\delta_0 + (1-2s)\,t\right] -$$

$$-\frac{1}{2}\varepsilon^{-2t/T_a}\sin 2\left[\delta_0 + (1-s)\,t\right] - \frac{1}{2}\sin 2(\delta_0 - st)\Big\} \quad (4)$$

where T_a = short-circuit time constant of the stator winding;
ε = base of natural logarithms; the other symbols are the same as in formula (2).

From formula (4) follows directly that a machine with an amortisseur winding on the rotor will be subjected to much less mechanical action than one without such a winding. This is because x_d'' and x_q'' differ little from each other when an amortisseur winding is present.

The maximum torque takes place when the machine is connected to the line at phase angles of 45 and 135 degrees.

Calculations have shown that in the case of machines not provided with amortisseur windings formula (4) yields accurate results for the first three to five periods of torque swings which are of particular interest in view of their influence on the unit.

In case of machines with amortisseur windings the values obtained for the torque by means of formula (4) are considerably lower than the actual values. However, calculations made with allowance for losses in the rotor circuits show that the values of the torques arising in these machines are not great, indeed.

Some torque-time curves in Fig. 1 relate to per-unit torques of a hydroelectric generator with an amortisseur winding arising at the instant of its connection directly

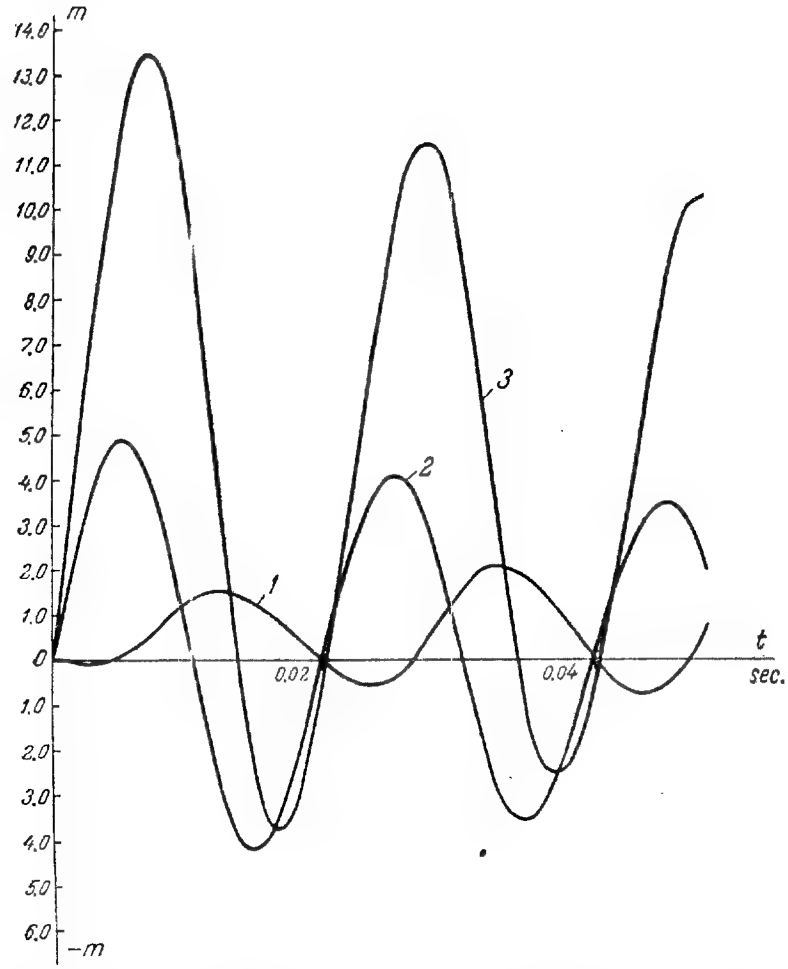

Fig. 1. Transient torque of a generator with amortisseur winding under different operational conditions.
1 — self-synchronizing; 2 — short circuit; 3 — asynchronous connection ($s = 0$; $\delta_0 = 135°$).

to a high-power line by the self-synchronizing method. Adjoined to them for the sake of comparison are torque curves plotted for the cases of a sudden three-phase short

circuit at the machine terminals and for the connection to the line of an excited machine with a phase-angle difference

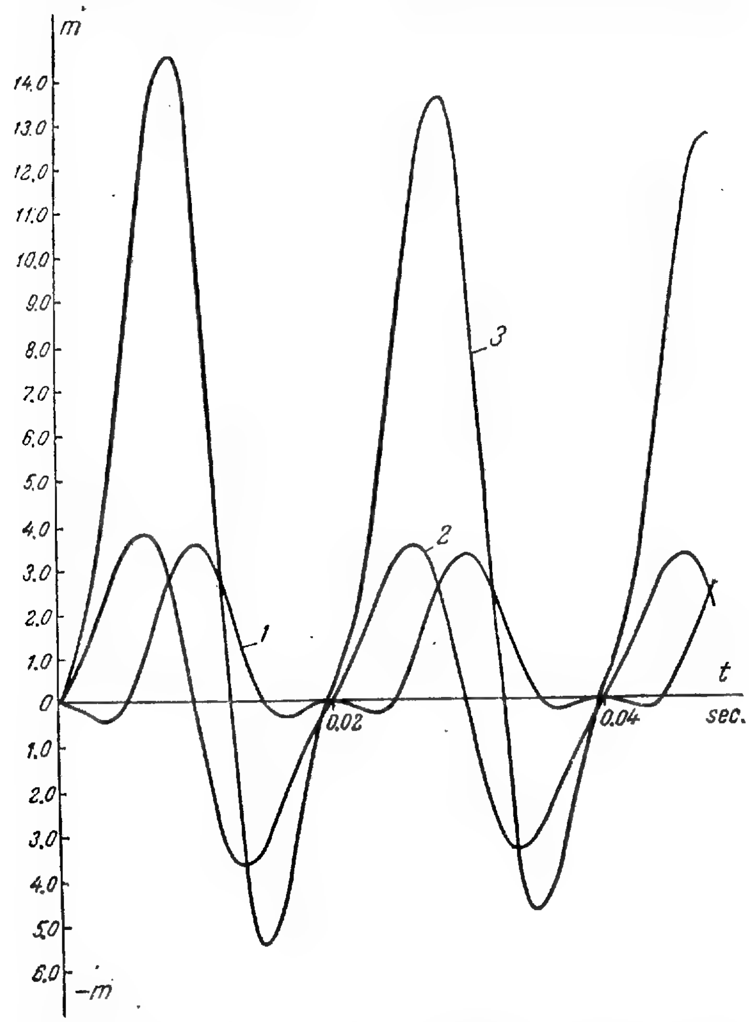

Fig. 2. Transient torque of a generator without amortisseur winding under different operational conditions.
1 — self-synchronizing ($s=0$; $\delta_0=135°$); *2* — short circuit; *3* — asynchronous connection ($s=0$; $\delta_0=135°$).

of 135 degrees. Similar curves for hydroelectric generators deprived of amortisseur windings are presented in Fig. 2. All curves are plotted on the same scale. Comparing them

we see that a machine with an amortisseur winding is subjected to a many times weaker mechanical action at self-synchronizing than in the case of a sudden short circuit and to a considerably weaker mechanical action than in the case where an excited generator is connected to the line with a large phase-angle difference.

In a hydroelectric generator which has no amortisseur winding the torque that arises following the connection of the generator to the line by the self-synchronizing method is, in the most unfavourable case, only slightly less in absolute value than the torque due to a sudden three-phase short circuit at the generator terminals. However, there is one essential difference. The self-synchronizing torque is of a pulsative nature and varies practically from zero to maximum in one direction whereas the short-circuit torque alternates in sign (Fig. 2). So in this case, too, the strain on the machine is less during self-synchronizing than during a short circuit. To support this conclusion it may be remembered that the allowable strain is greater with a pulsative load than with an alternating sign load[7,8].

When there is an external resistance, the torque acting on the machine is reduced considerably. Thus, if the same generator without an amortisseur winding is connected to a high-power line by the self-synchronizing method through a corresponding power transformer (generator-transformer bank), the amplitude of the torque will be reduced to 1.8 of its rated value. This is considerably less than the amplitude of the torque acting on a sudden short circuit at the machine terminals. Transmitted to the shaft between the generator and the prime mover is only a small fraction of the electromagnetic torque which in first approximation is equal to the ratio of the WR^2 of the prime mover to the WR^2 of the whole unit. In hydroelectric units where the electromagnetic torques may be the largest this ratio is very small (about 0.05 — 0.1).

It may be inferred that even in the most unfavourable cases of self-synchronizing the generators are subject to

a weaker torque action compared to that which a machine is designed to sustain without damage when a sudden three-phase short circuit occurs at its terminals. On the other hand, the torques that arise when an excited machine is faultily connected to a high-power line are several times as large as short-circuit torques, and so they are apt to cause damage.

When the generator field is applied, the electromagnetic torque under consideration will be superimposed by a torque due to the increasing excitation current.

If the generator field winding is connected to an already excited exciter, we may assume for practical purposes that the emf and, hence, the amplitude of the torque increase with the time constant T_d' according to an exponential law. On the other hand, if the voltage across the exciter starts to increase simultaneously with its connection to the generator field winding, the rate of increase of the torque will be correspondingly lower.

SOME PROBLEMS CONCERNING THE PULLING OF GENERATORS INTO SYNCHRONISM

It is not our task here to give a full analysis of the process by which generators pull into synchronism; only certain main factors upon which a successful completion of this process depends will be discussed and some practical recommendations will be made relative to the use of the self-synchronizing method.

One of the main factors in determining a successful pulling of a generator into synchronism is the average asynchronous torque, as has been mentioned previously. To secure a reliable synchronization this torque must exceed the possible surplus mechanical torque created by the prime mover at the moment the non-excited generator is connected to a line. Such a surplus torque will take place, for instance, if the generator is connected to the line while accelerating above synchronous speed.

The greater the asynchronous torque the easier a machine connected to a line with a certain slip is approach-

ing synchronous speed and pulls into synchronism owing to the reactive torque or the torque due to excitation.

Average asynchronous torque characteristics of a steam turbine-generator, a hydroelectric generator with an amortisseur winding and one without such a winding are plotted for comparison in Fig. 3. Other conditions being equal,

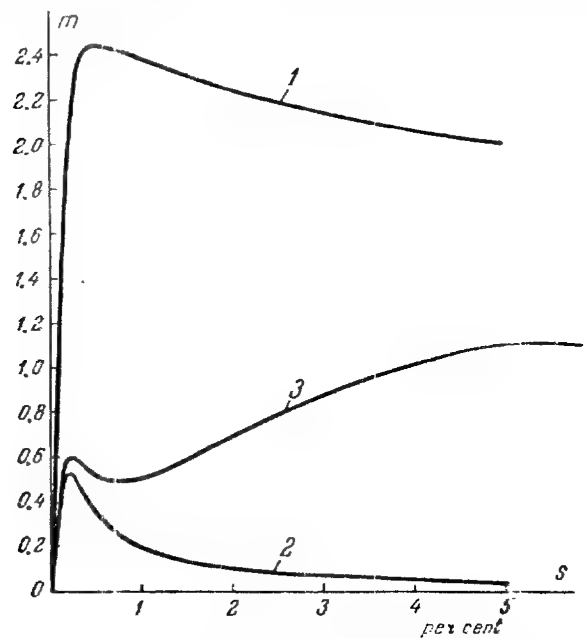

Fig. 3. Average asynchronous torques for different types of synchronous generators.
1 — for a steam turbine-generator; 2 — for a hydroelectric generator without amortisseur winding; 3 — for a hydroelectric generator with amortisseur winding.

the asynchronous torque of any generator increases with a decrease of the external reactance inserted between the line and the generator.

Steam turbine-generators show the best torque characteristics. When connected to the line by the self-synchronizing method they synchronize within 2—3 seconds even if the slip ranges from 15 to 20 per cent.

Naturally enough, with so large a value of the average asynchronous torque there is no need to take special

measures for limiting the value of the surplus torque in the turbine in order to provide for a reliable synchronization of the steam turbine-generator. In fact, such generators synchronize irrespective of starting characteristics generally used in practice.

For hydroelectric generators without amortisseur windings the average asynchronous torque characteristics are not so favourable. Nevertheless, as calculations and experience show, it is possible to secure conditions under which these generators will reliably synchronize. In many cases this can be achieved by choosing an appropriate initial opening of the gate apparatus, and only in rare cases some simple measures are necessary to limit the surplus torque at the end of the starting period. This is attained by providing the automatic arrangement with starting elements which act either on the opening limiter[9] or on the speed controlling mechanism of the turbine regulation[10,11].

It stands to reason that no special measures are needed to secure the pulling of synchronous condensers into synchronism since the conditions of their synchronization are by far more favourable than with generators owing to a practically complete absence of surplus torque of the prime mover.

Other conditions being equal, the process of synchronization takes the more time the greater the slip at which the generator is connected to the system. The value of the slip must be so chosen as to secure rapid self-synchronizing and to avoid unnecessary complications in the approach to synchronous speed and in the speed control at the instant of connection. In a normally operating system these conditions will be satisfied if the slip ranges within $\pm 2.0 - 3.0$ per cent; in case of emergency during frequency oscillations in the line, connection with a slip as large as ± 5.0 per cent is allowable. It may be emphasized that there is no danger to the machine if it is being connected at a larger slip, but then the pulling into step lasts longer.

It is important to consider the moment of the field application and the excitation value of the machine. Calculations and experience show that with the slip values recommended above it is well to apply excitation just after the machine is connected to the line. The easiest way to effect this is by closing the field circuit by the automatic discharge switch through the locking contacts of the generator circuit breaker. The excitation rheostats of the exciter are supposed then to be in the operating position, corresponding to the particular type of the excitation regulator installed on the machine. It is not expedient to limit the excitation value since with large excitation values the generator (synchronous condenser) pulls into synchronism more rapidly, the line voltage is sooner restored, and the generator (synchronous condenser) begins earlier to give off its reactive power to the system. Therefore, if the synchronous machine is connected in parallel by the self-synchronizing method, the automatic excitation control devices must remain in operation in order to force the excitation if there should be a considerable voltage drop on the line at the instant of connection.

A simultaneous application of the field with the connection of the synchronous machine to the system is desirable because salient-pole machines, if a delay of excitation occurs, may pull into synchronism by a reactive torque with a polarity that would not correspond to the polarity of the magnetic field created by the excitation. In such cases the machine after the application of the field will fall out of step for some time — its rotor turns through an angle of 180 el. degrees relative to the stator field — and then pulls into step again with some hunting. This will not occur if the field is applied previous to synchronization. Moreover, the delay of excitation implies a more complicated arrangement for supervisory control and automatization of the connection-to-the line process.

When salient-pole machines deprived of damping circuits are being connected to a system, rather large and

slowly decaying hunting is sometimes observed. This is because such machines are in general liable to hunting under no load conditions, irrespective of self-synchronizing, owing to the smallness of their damping torques at angles δ approaching zero. This hunting is dangerous neither to the machine nor to the system and is rapidly damped after loading by the increase of the damping torque. In machines with damping circuits the hunting decays rapidly even under no load.

It is interesting to consider now the influence of the prime mover speed regulators upon the synchronization process. With the slip values recommended above the pulling into synchronism is usually so rapid that the prime mover speed regulators which in conjunction with all service mechanisms possess a rather great inertia have no time to affect the synchronization process appreciably. However, the subsequent behaviour of the generator depends greatly on the operation of the speed regulator.

If, at the instant of connection, the speed regulator is in a position corresponding to a speed higher than synchronous speed, then at synchronism the gate mechanism of the prime mover will open, and the unit will furnish active load to the system. If the excitation is applied too late or is growing very slowly, the increased active load may exceed the reactive torque of the generator, and the latter will again fall out of step. But, practically, this does not occur if the field is applied in time.

If the load taken automatically is for some reason considered to be too high, it can be easily reduced by manual operation or by means of supervisory control equipment in automatized stations.

On the other hand, if at the instant of self-synchronizing the speed regulator is in a position corresponding to a speed lower than synchronous speed, then after the generator synchronizes the speed regulator will partly or even completely close the prime mover directing device, and the generator will take active power from the line while operating as a motor. In such cases it is necessary

to secure conditions where the generator gives off some active load.

The second case is not attended with any danger, yet it is obvious that the first case is preferable. Therefore, it is better to effect the connection when the automatic speed regulator is in a position corresponding to a higher than synchronous speed, or at any rate to secure conditions under which the generator after its connection to the line would in the shortest possible time give off some active power to the system even though in small quantities.

INFLUENCE OF LINE VOLTAGE DROP AT SELF-SYNCHRONIZING ON THE OPERATION OF THE POWER SYSTEM AND POWER CONSUMERS

In modern power systems of great capacity the line voltage drop caused by the use of the self-synchronizing method in connecting generators to the line is in a great majority of cases so small as to pass unnoticed.

Considerable line voltage drops (up to 50 per cent) take place only if the generators connected to the line by the self-synchronizing method are comparable in power to the operating generators. Voltage drops of similar magnitude may occur in the auxiliaries fed through a branch circuit (Fig. 4) from the terminals of a self-synchronizing generator if there is its own circuit breaker.

Experience shows that if the operating generators, as well as the one which is being connected to the system, are provided with an automatic control of the excitation (which is the usual case nowadays), the voltage will be restored to its initial value in 2—3 seconds.

With such short-time voltage drops no operational disturbance is occasioned as a rule to the system or to consumers.

Therefore, there is no limitation to the power of generators that can be connected to the line by the self-synchronizing method nor to the value of the possible voltage drop produced by the connection.

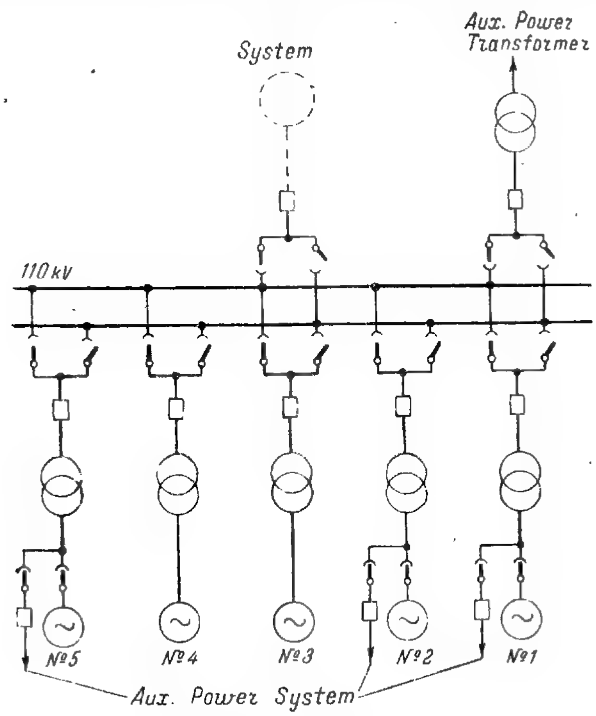

Fig. 4. Single-line diagram of a station with a branch circuit for the station auxiliaries.

THE RECOMMENDED USE OF THE SELF-SYNCHRONIZING METHOD

When there is a drop of voltage or frequency in the system, the self-synchronizing method should be applied to any given generator.

In a normally operating system this method is fit to be applied to any salient-pole machine (generator or synchronous condenser) irrespective of its power or of the connecting arrangement. It is also applicable to cylindrical rotor generators whose power output amounts to 3,000 kw inclusive, and to even more powerful generators working in generator-transformer banks. With regard to cylindrical rotor generators above 3,000 kw which are connected to the system at the generator voltage the ques-

tion whether the self-synchronizing method can or cannot be applied as a normal practice in bringing them to in-step operation with a system must be decided for the given system and generator individually on the basis of special tests.

It may be advised to use the self-synchronizing method in conjunction with automatic reclosing (ARS) for radially arranged lines connecting the power station with a system. The restoring sequence of the connection to the system is then as follows:

a) When the transmission line is put out by a short circuit, the field of the station generators is discharged; the generators can thereby be automatically disconnected from the station buses or can be left connected to them.

b) Some time later the line is automatically reclosed; if at that time the short circuit is cleared, voltage re-appears at the station buses giving closing impulse to the generator circuit breakers (all generators at a time or in sequence) if they are off, or to the generator field discharge switches if the generators are not disconnected from the buses; after the excitation is thus restored the generators pull into synchronism.

If the station has a local load which does not permit the energy supply to be interrupted even for a brief space of time, to a part of the generators disconnected off the system can be assigned the task of power supply while the rest will be involved in the reclosing procedure just described.

The length of the interruption time can be chosen to equal the interval during which the speed of the generators having attained a maximum after the throwing off the load is reduced by the speed regulator to its rated value (Fig. 5,*a*). For hydroelecrtic stations this time interval ranges from 15 to 40 seconds. To shorten the time of return to normal operational conditions the reclosure can be effected within an interval sufficient for the generator voltage to be reduced to about 0.20 — 0.25 of its rated value. Therewith the generators will sometimes be

connected to the line at a relatively large slip before maximum speed is attained (Fig. 5,*b*). While rotating faster than synchronous speed the generators will give off active power to the line and so will slow down more rapidly than in the first reclosing scheme. An amortisseur winding will add to the slowing down effect because of asynchronous torque whereby the time of return to normal will be reduced essentially. With this reclosing scheme

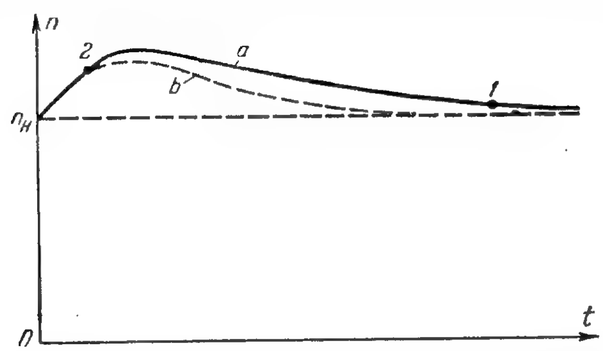

Fig. 5. Speed variation of a hydroelectric generator on throwing off load.

a — under the action of a speed regulator; *b* — under the action of a speed regulator and an asynchronous torque.

the field of hydroelectric generators should not be restored before they come to synchronous speed since the field current grows much faster than reduces the slip to a value at which the pulling of the generator into synchronism is possible. An asynchronous rotation of an excited generator leads to large swings of power, current and voltage. These swings are particularly large with a forced excitation.

The choice between these two schemes of ARS for a given hydroelectric station depends on local conditions. One of the considerations is the ability of the system to withstand the voltage drop due to the consumption of reactive power from the line during the asynchronous operation of the generators. For steam turbine-generators the second scheme may always be recommended as it is more simple. The increase of their speed after the load

is thrown off is not great (no more than 10 per cent), and, as has been mentioned before, they develop a large asynchronous torque. Therefore, the time interval during which they are coming to synchronous speed is very small, and so there is no need to delay the application of the field which can be restored just after the connection of the generator to the line.

DEVICES INVOLVED IN CONNECTING GENERATORS BY THE SELF-SYNCHRONIZING METHOD

According to what has been said here the use of the self-synchronizing method implies that the following operational conditions be secured by the devices and circuits involved:

a) The generator is connected to the line unexcited with the field winding paralleled by a discharge resistance and with a definite slip; the slip is usually adjusted at about $\pm 2 - 3$ per cent in normal operating conditions and at ± 5 per cent if the frequency in the system is falling or oscillating.

b) The field is applied immediately after the generator is connected to the line; the automatic field regulators must never be out of operation unless for some reason not related to self-synchronizing.

c) In case of hydroelectric generators deprived of amortisseur windings the surplus torque created by the prime mover should be small enough for reliable synchronization.

To control the slip at the instant when the generator is being connected to the line by the self-synchronizing method a special type of relay (induction type of frequency difference relay) was designed and is now produced on a commercial scale (IFD-01); this slip relay is connected to the residual generator voltage and to the line voltage[12].

With this relay schemes of manual, semimanual and automatic self-synchronizing have been worked out and introduced into practice[12].

Manual and semimanual self-synchronizing is used at steam power stations of any power and at small rural hydroelectric stations not yet automatized.

FIELD EXPERIENCE WITH THE SELF-SYNCHRONIZING METHOD

At present the self-synchronizing method, from the information available which is not complete, is used as a routine operation with more than 160 generators and 15 synchronous condensers provided with starting motors.

The generators at which self-synchronizing is applied vary in power within a very wide range from a few tens to 90,000 kva. Some of the self-synchronizing condensers have a power output ot 30,000 kva.

Experience shows that the range of applicability of self-synchronizing includes generators with prime movers of any kind (steam turbines, hydraulic turbines, internal combustion engines, locomobiles, wind motors, etc.). This method has also proved a success with twin aggregates of the Jungstrem type. Tests made by the Southern Department of the Scientific Consultative Organization for Maintenance and Automatic Control of Power Stations have shown that these units can be connected to the line even if the rotors of the two generators are asynchronously rotating; both the turbine and the generators behave quite normally.

Self-synchronizing has greatly contributed to a successful solution of the automatization problem as regards the connection of generators to the line at hydroelectric stations and has considerably shortened the duration of this process. The latter practically lasts not longer than the time required to attain nearly synchronous speed. At many hydroelectric stations the generators are on the line not later than in a minute after the impulse is sent to start the unit, and at some stations this interval is reduced to 20—30 seconds.

At power stations of low capacity (about a few thousands of kilowatts and lower) self-synchronizing is often used with generators of equal power operating apart from

a system and even for bringing a higher power generator into parallel operation with small-power generators, the power ratio being sometimes 2:1. It should be noted that at many power stations of low capacity the prime movers are not provided with speed regulators, and parallel operation of generators was not used there at all before the introduction of the self-synchronizing method.

At some hydroelectric stations self-synchronizing has been in use for several years. Many generators have been brought on the line by this method hundreds and even thousands of times.

At one hydroelectric station, for instance, each of its two generators of 17,500 kva, 10,5 kv, 150 rpm has been connected to the line by this method more than 2,500 times. Operational experience and thorough periodic examinations have shown that they are both in good condition.

At steam power stations self-synchronizing has been used, as a rule, with generators operating in bank with transformers; the power output of generators at which this method is applied ranges up to 50,000 kw. And at these stations as well the accumulated evidence has proved that self-synchronizing is a simple and convenient method.

For example, the self-synchronizing method has been in use since 1951 at a power station having four 30,000-kva and one 44,000-kva generator (the single-line diagram of this station is shown in Fig. 4); each of the generators has been brought on the line by the self-synchronizing method 25 to 45 times. The station has also retained its precise synchronizing equipment.

At another station with a similar network arrangement having 50,000-kw generators self-synchronizing has also been in use since 1951, and each of its generators has been brought on the line from 30 to 50 times.

At none of the stations where the self-synchronizing method was applied have any departures from normal been observed in the operation of generators or turbines or of the station auxiliaries.

CONCLUSIONS

Experiments and practice show that self-synchronizing is a very convenient method of connecting generators in parallel. It greatly simplifies this process, shortens its duration, permits it to be easily automatized and excludes any possible damage to the machine by faults that might occur on its connection to the line in an excited state.

Therefore, this method should become widespread for synchronous condensers with auxiliary motor starting and for generators of any design and power.

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AUTOMATIC RECLOSING IN HIGH-VOLTAGE NETWORKS

by

M. I. Tsarev, P. K. Feist and A. B. Chernin

This paper describes the principles of automatic reclosing (AR) of high-voltage lines, used in the power systems of the Soviet Union.

Discussed are also the development and design of single-phase and three-phase automatic reclosure devices and statistical data which show their efficiency in operation. These data have been obtained on the basis of experience in operating a large number of different types of AR installations for the last five years.

Special attention is given to problems of single-phase automatic reclosure (SAR): the basic types of discriminating elements in SAR installations which select the faulted phase of the line are reviewed in detail; the requirements they are to satisfy and the principles of selecting their characteristics are also discussed.

The recent trend to use complex automatics on important transmission lines including different types of AR is called to attention.

INTRODUCTION

Automatic reclosing in high-voltage networks contributes most effectively to the reliability of power supply to consumers and reduces the number of outages in the system.

In the Soviet Union the use of some kind of automatic reclosing is considered as obligatory on every line with a tension of 2 kv or higher.

Three-phase automatic reclosure (TAR) is used on all lines ranging in voltage from 2 to 220 kv, in networks with both large and small ground-fault currents. TAR is also used for transformers and buses of high-voltage substations.

According to the method by which the high-voltage circuit-breakers are controlled, the TAR arrangements may be subdivided into two groups: mechanical TAR (with loading-weight, spring type, etc.) used for manually controlled circuit-breakers and electrical TAR used for remotely controlled circuit-breakers.

Those of the first group are hand-reset and are designed for single reclosure operation. Most of the second group have an automatic reset and can be designed both for single and multiple reclosures. In the U.S.S.R., however, single reclosure is more widely used for the present time.

Single-phase automatic reclosing (SAR) is used for overhead lines of 110—220 kv in networks with a large ground-fault current and in installations having remote control of high-voltage circuit-breakers. As a rule, the automatic tripping of one phase and its reclosing are performed only in case of single-phase short circuits. In all other cases of line faults all the three phases are opened. On that account, in order to increase the efficiency of automatic reclosing, TAR is used along with SAR. This is the most effective way to

solve the problem since in the majority of the fault cases on the transmission line the opening of only one phase is thereby secured, and only in comparatively rare cases all of the three phases are tripped and reclosed automatically.

Most important to a successful operation of TAR in the main network of a power system is a high speed of operation of relay protection following the AR since this simple measure secures a stable operation of the system.

Statistical data on operation of many thousands of AR installations used on transmission lines in the U.S.S.R. for the last five years show that every TAR set in a power system prevents an interruption of power supply to consumers once in a period of 1.5—1.75 years.

The percentage of successful TAR performance as an average is 69 in the case of single reclosure and 77.3 in the case of double-reclosure installations. Successful operations in the second cycle make up about 16 per cent. It should be noted that successful TAR operations as an average make up 52 per cent on 2—10-kv cable lines and 58 per cent on mixed lines (overhead lines and cables). Most of the faults successfully cleared by TAR on cable and mixed lines were due to the damage of the equipment connected to the line. In the first place, supporting insulators, disconnecting switches, power transformer bushings, etc. were the responsible cause.

The percentage of successful SAR operations is 73.6 for 110-kv lines and 78.0 for 220-kv lines.

Failures to operate due to various reasons make up 1.15 per cent of all the cases of AR operation (i. e., of the total of successful and unsuccessful operations). This is the average figure for five years.

The automatic reclosing of transmission lines, securing an uninterrupted supply of power to consumers in many cases affords the possibility of simplifying the schemes of relay protection and increasing the speed of its operation. Non-selective operation of the relay protection may be allowed on one or several sections of the network

if a non-selective tripping is corrected immediately by automatic reclosing of the wrongly opened line. This method is widely used in the power systems of the Soviet Union and has proved to be very efficient.

THREE-PHASE AUTOMATIC RECLOSING

The three-phase automatic reclosing of transmission lines has been practised in the Soviet Union for above 20 years. During this long period a large operating experience has been accumulated, in particular on its design which involves the solution of many specific problems. First to be mentioned are these: providing a reliable start, preventing repetitive reclosures in case of a stable short circuit, control of the absence of voltage on tie feeder lines, control of synchronism of voltages.

For the electrical type of TAR two methods of starting are used at the present time:

1. The starting impulse is received from the protective relay system.

2. The starting impulse is received from a circuit energized when the position of a high-voltage circuit-breaker does not correspond to that of its controlling switch.

The second method is more reliable and is effective in cases when the circuit-breaker has tripped because of some mechanical reasons (vibration or some defect in the operating mechanism). Besides, the AR devices are more simple in design and maintenance. However, considerable difficulties are encountered when this starting method is applied to supervisory and automatically controlled units.

The prevention of multiple reclosures in case of a stable short circuit is likewise secured by different methods; for instance, the electric schemes are so designed that no repetitive reclosures take place if anyone of the TAR elements is out of order.

On tie feeder lines the TAR equipment is provided with special interlocking elements which prevent automatic reclosure on one side when the line is alive and on the other

side when the separated parts of the system are out of synchronism, or their voltage vectors divergence angle is inadmissible.

The control of the absence of voltage on the line, i. e., of the opening of the circuit-breakers on both sides of the line, is usually effected by means of an undervoltage relay which is connected to one of the line phases. If a potential transformer is not available, special potential devices are used for voltage take-off from the line; this involves the use of condenser type bushings of high-voltage circuit-breakers, of coupling capacitors for carrier-current protective relaying or for communications along transmission lines.

The control of the divergence angle between voltage vectors or of the voltage synchronism is effected by means of a special relay which responds to a change of angle between two magnetic fluxes. Usually the synchronism controlling relay has one of its windings connected to the potential transformer installed on the buses of the power station or substation, while its other winding is connected to a potential transformer (or a capacitor potential device as described above) connected directly to the line.

Two methods of TAR with control of synchronism are practised. One of them is used on lines having several parallel connections; it consists in preventing the TAR if after the re-connection of the faulted line from the opposite end the divergence of the voltage vectors is surpassing the admissible angle.

The second method is used on single lines or on lines having only one parallel connection; it consists in "waiting" for the instant when the voltages are brought into synchronism. When the conditions are close to synchronism with an admissible beat period, the circuit-breaker is closed by the AR device. Thus, the TAR arrangement of this kind operates like an automatic synchronizer.

If the line is equipped with high-speed circuit-breakers and the complete cycle from opening to reclosing by the AR device does not exceed 0.25—0.3 sec., TAR without

voltage synchronism control is used on tie feeder lines whenever the conditions for stable operation of the system admit it.

SINGLE-PHASE AUTOMATIC RECLOSING

The isolation of only the faulted phase, in case of line-to-ground faults, and its subsequent automatic reclosure (SAR), is extensively used in the Soviet Union on 110- and 220-kv lines with large ground-fault currents. It has been employed particularly often on single trunk feeder lines (between stations or between parts of a system) whenever the three-phase automatic reclosure was for some reason impracticable. Sometimes SAR (in combination with TAR) has been used on heavily loaded parallel 110—220-kv tie feeder lines.

SAR is provided also for 440-kv transmission lines under construction in the U.S.S.R.

On tie feeder lines SAR is arranged, as a rule, in such a way as to disconnect the line entirely in the event of a stable fault at the reclosed phase. However, in certain cases of unsuccessful action of SAR of a tie feeder line, the isolation of only the faulted phase and operation of the line for a long period of time with its two (or five, in case of two parallel lines) undamaged phases has been practised in recent years.

SAR has been widely used in combination with TAR on radial lines. Here, too, only the faulted phase is isolated, and the line is continuously operated with two phases if the reclosure after fault fails. On radial lines SAR is often set to operate not only for line-to-ground faults but for phase-to-phase faults as well. Thus, in the event of this kind of fault, too, only one of the two faulted phases is opened and reclosed.

Sometimes such an application of SAR is also used on tie feeder lines.

Whenever SAR is in service, the protective relay equipment must secure the selection and isolation of only the faulted phase in case of a phase-to-ground fault (or, sometimes, of

only one of the two faulted phases in case of a phase-to-phase fault). For this purpose special discriminating elements are usually provided.

In other cases of short circuits all the three phases of the line are disconnected. Then the SAR is designed in such a way that in case of a phase-to-phase fault the protective relays will disconnect the line irrespective of the operation of the discriminating elements.

As investigations have shown, modern protective relaying schemes with high-frequency (carrier-current) interlock used in the U.S.S.R. on high-voltage lines may fail to operate for faults when the line works under two-phase (of five-phase) operating conditions. In this connection the discriminating elements of the relaying equipment are assigned the function of independent protection of the line from the instant at which the faulted phase is disconnected to the end of the SAR cycle. It should be noted that with this added task imposed on the discriminating elements the SAR installation becomes considerably complicated and has to satisfy higher requirements.

In the Soviet Union considerable and fruitful work has been done on the research and design of discriminating elements for various conditions of SAR application.

The problem of selecting the faulted phase on radial lines is solved by the use of discriminating elements involving simple current relays, voltage relays and power directional relays.

The solution of this problem for tie feeder lines is much more complicated.

On these lines two types of discriminating elements have been used in the U.S.S.R.:

1. A combined, filter type, discriminating element.
2. A distance type discriminating element.

As is well known, a discriminating element involving three power relays designed to respond to currents (or voltages) of negative and zero sequences is unable to discriminate between single and double phase-to-ground faults.

Therefore, it will be inapplicable unless the protective relays of the line can discriminate independently between these two kinds of fault.

Now, the protective relaying schemes with carrier interlock operating for all kinds of fault, as provided for high-voltage lines in the Soviet Union, will operate for a ground fault irrespective of whether one or two phases are involved. Therefore, a discriminating element of the combined filter

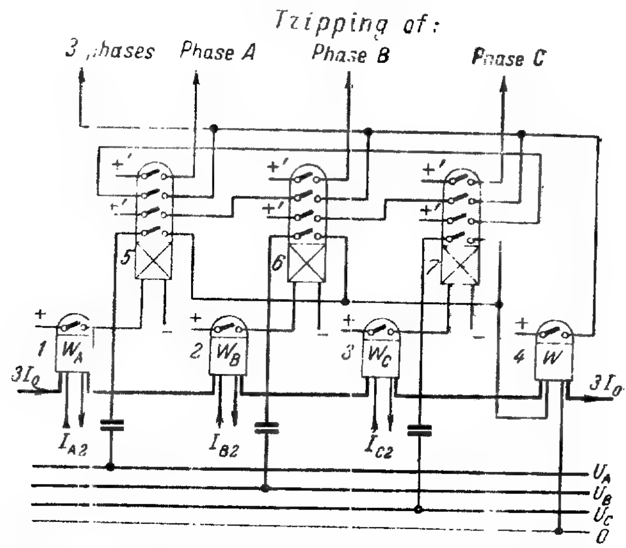

Fig. 1. Combined filter type discriminating element.

type (its schematic diagram is shown in Fig. 1) has been developed and has become widespread in the U.S.S.R. It is a combination of three power directional relays (relays *1*, *2* and *3*) responsive to negative and zero sequence currents (or voltages) and a power directional relay responsive to zero sequence current and to phase voltages (relay *4*).

If only one phase is involved in a ground fault, a distinct discrimination of this phase is secured by the respective relay: *1*, *2* or *3*. If two phases are involved in a ground fault, a complete disconnection of the three phases of the line is

effected by relay *4* to which the voltage of the undamaged phase is applied.

Special investigations have shown that in case of double phase-to-ground faults through a large fault resistance two of the relays *1—3* may respond. In that case, owing to the failure of relay *4*, a disconnection of the three phases of the line is secured by a cyclic combination of the contacts of intermediary relays *5—7*, which are actuated by relays *1—3*.

The main drawback of the combined filter type discriminating element is its comparative complexity due mainly to the unavoidable insertion of special electrical interlocks. Indeed, for a successful reclosure of the opened phase, restraint by means of current relays inoperative for the capacitive current of the line is necessary. If the magnitude of the capacitive current is large, the choice of the current that will start these relays is complicated; it makes the realization of this interlock a matter of considerable difficulty.

Another interlocking appliance should be provided to make the discriminating element inoperative during a possible consequent disconnection ("cascade tripping") of the faulted phase in case of a phase-to-ground fault. This is necessary because relays *1—3* after disconnecting the phase-to-ground fault at one terminal of the line may change orientation and select one of the undamaged phases. By bringing the discriminating element out of operation all the protective relaying elements disconnecting the line through the SAR devices are made inoperative for this period. This is, of course, undesirable since it will delay the disconnection of the line in case of a possible extension of the fault to the other phases.

Discriminating elements of the distance type include three resistance relays responsive to phase voltages and currents. They discriminate between single-phase and double phase-to-ground faults because in the first case only one of the resistance relays comes into operation while in the second case two relays operate. When not all the phases of the line are in operation, the contacts of the resistance relays are

opened provided the emf divergence angle of the generators at the ends of the system does not surpass a certain limit. Special restraining interlocks necessary in the case of the combined filter type are here superfluous; in this way the SAR schemes on tie feeder lines can be considerably simpli-

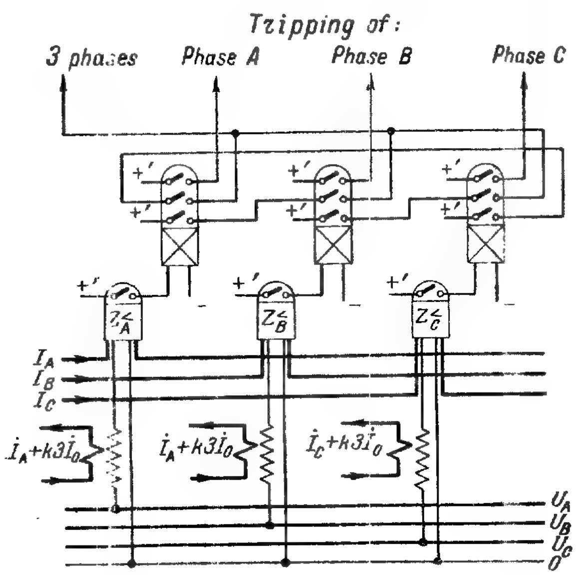

Fig. 2. Discriminating element with compensated distance relays (responsive to phase currents).

fied and will be more reliable in operation. This will improve the operation of the relay protection of the line.

It is owing to these advantages that discriminating elements of the distance type have been used on an ever increasing scale.

The resistance relays are designed to have characteristics representable in the total resistance complex plane as circles with centres displaced from the origin.

Two connection diagrams for these relays are known.

According to one of them (Fig. 2) the relays are connected to respond to phase currents and phase voltages compensated by current $\dot I_p + k3\dot I_0$ where $\dot I_p$ is the total current of the respective line phase and $\dot I_0$ is its zero sequence component.

According to the other scheme (Fig. 3) the relays are connected to respond to the same voltages and current $\dot{I}_p + k3\dot{I}_0$.

The discriminating element in Fig. 3 has some advantages compared to that in Fig. 2, namely:

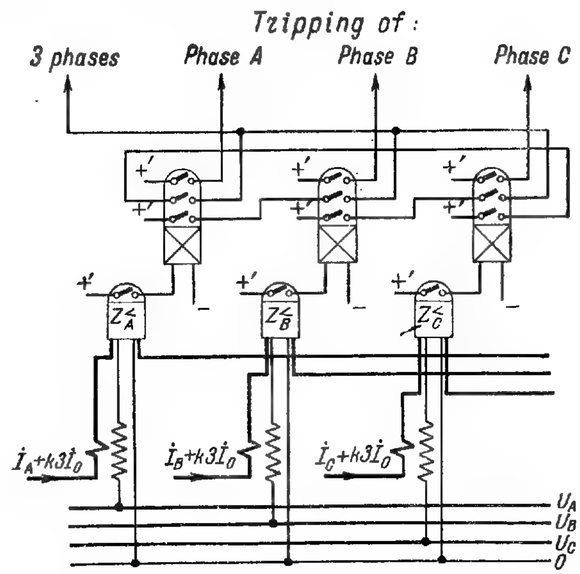

Fig. 3. Discriminating element with compensated distance relays (responsive to current $\dot{I}_p + k3\dot{I}_0$).

1. In case of single-phase or double phase-to-ground faults the resistance at the faulted phases relay terminals is equal to the positive sequence total resistance of the faulted line section.

2. The operation characteristic of the relay displaced by the compensation of the voltage applied to the relay does not depend on the connection scheme or on the operating conditions of the system.

Therefore, the operation of discriminating elements thus arranged is easy to analyze and depict. A study of their operation conducted on several long and heavily loaded 220-kv lines has shown that they secure a reliable discrimination of faulted line phases in case of single-phase and double phase-

to-ground faults and are less dependent on the value of fault resistances compared to the discriminating elements shown in Fig. 2.

Comparative studies on 400-kv transmission lines (Kuibyshev-Moscow) have shown that with the discriminating element arranged according to Fig. 3 the relays are restrained more reliably against operation for hunting currents during a cycle of SAR when one of the line phases is out of operation.

As has been mentioned above, the resistance relays of the distance type discriminating element are chosen to have a circular characteristic in the complex plane. To eliminate a dead zone when the fault occurs at the beginning of the line the relay characteristic must comprise the origin.

However, if the characteristics are so chosen, difficulties may arise with the scheme in Fig. 3 in securing the selectivity of the relays controlling the undamaged phases in the case of single-phase faults occurring near powerful sources of electric energy This is determined by the large value of the zero sequence current. To remove the above difficulties we have either to insert an additional saturation appliance in the circuit of the zero sequence current or so to shift the resistance relay characteristic as not to let it include the beginning of the line In the latter case the faults arising within the usually small unprotected line section close to the beginning of the line can be yet dealt with successfully if we use either current relays of the instantaneous phase overcurrent cut-off or specially inserted current relays responsive to total phase currents of the line.

Sometimes, because of a change in the operational conditions of the system or in its connections, the magnitude of the currents due to a single phase-to-ground fault occurring close to the beginning of the line may change sharply; in such cases undervoltage relays responsive to phase voltages must be added to current relays.

A serious problem with the distance type discriminating elements to be solved is the possibility of their operation for

hunting, which may arise when there is phase divergence between the emf of the generators in a SAR cycle. Their behaviour towards hunting is important because the discriminating elements are, as has been mentioned above, assigned the functions of an independent protective appliance in case of faults when only two line phases are in operation or in case of an unsuccessful reclosure of the isolated phase.

Some increase in selectivity of the discriminating element for hunting will be obtained if we choose the relay characteristic to have an elliptical or oval form instead of circular or if we choose it in the form of two intersecting circles one of which does not embrace the origin.

With the field of its operation thus narrowed the relay may operate unsatisfactorily in case of faults through large fault resistances. Computations for 220- and 400-kv lines show that sometimes, on the occurrence of a single phase-to-ground fault, the fault resistance value to which the discriminating element relays will still respond simultaneously on both sides of the line is limited to 10 or even less ohms.

After the faulted phase is disconnected on that end of the line where a larger current flows to the fault and where conditions for the operation of the relays are therefore better the relays on the other side also get more favourable conditions for operation. For that reason in the latest SAR installations in design and in service in the Soviet Union a possibility of consequent (cascade) operation of the discriminating element resistance relays is provided. For that purpose the tripping circuit of the three line phases is closed with some delay when the discriminating element fails to respond to a single-phase short circuit.

Extensive research has been under way in the Soviet Union on conditions under which a continued operation of a high-voltage tie feeder line is possible when not all of its phases are at work. The main difficulty here is to secure a correct operation of the relay protection.

Added significance acquires then a fact mentioned earlier, viz., that the main carrier-current protective relaying may,

fail to operate in a SAR cycle if the line is allowed for a time to continue working with two phases only. The study of measures intended to solve this problem is in progress:

Most of the back-up protective devices responding to a voltage, current or power of negative and zero sequences respond to the isolation of a single phase in the way as if this phase were involved in a phase-to-ground fault. Under continued two-phase operation of the line the proper time-setting for these operating conditions cannot be selected. The possibility to select the proper sensitivity-setting depends on the value of power transmitted along the two working phases and on the connection diagram of the system.

If conditions are favourable, this setting can be selected without surpassing the allowable lower limit of sensitivity. Then a continued two-phase operation will be as possible for tie feeder lines as it is for radial lines.

In other cases considerable difficulties are encountered, and the solution involves a serious limitation of power transmitted by the line.

In principle, it is quite possible to develop for tie feeder lines such SAR devices as will secure their automatic transition to two-phase operation when one of the phases is involved in a stable ground fault.

Continued operation of this kind is not the usual practice in the U.S.S.R but it has been used on occasion.

CONCLUSIONS

1. In the Soviet Union a long-year experience with a great number of variously arranged automatic reclosure sets has furnished abundant evidence in favour of this kind of power system automatic control. Automatic reclosing is very effective in decreasing troubles in power systems and in increasing the reliability of operation.

2. There has been a growing tendency in recent years to apply complex automatic control, first of all SAR in combination with TAR and also TAR in combination with self-synchronization.

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314. — CONTRIBUTION TO THE PROBLEMS OF THE EARTH WIRE OF A PROTECTIVE ZONE ADJACENT TO A SUBSTATION.

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SUMMARY

The report examines the results of a lightning stroke to a protective zone, fitted with an overhead earth wire, adjacent to the station. Starting from the general equations for multi-conductor systems certain cases of particular importance are examined. In the conclusions reached the importance of avoiding back flashover is confirmed; the efficacy of the earth wire for the protection of the station in the case of a direct stroke to the protective zone is demonstrated; the importance of connecting the earth wire to the general earthing system of the station is underlined; and the absence of any danger due to a high coupling factor is pointed out.

REPORT

1. INTRODUCTION

The installation of a protective zone with overhead earth wires adjacent to a substation gives *two advantages* for the protection of the station against atmospheric overvoltages, viz.

a) A limitation of the discharge currents in lightning arresters or protective condensors in the station;

b) A limitation of the steepness of incident surges.

The effect *A* is of secondary importance for modern lightning arresters because of considerable improvements in their discharge capacity. Condensors, on the other hand, produce a satisfactory protection only (in particular for generators) if the incident currents are not excessive. The effect *B* plays an important part in the insulation co-ordination of large transformer stations. The actual margins in a system of insulation co-ordination are small so that inductive voltage drops in the station may affect seriously the protection of equipment at some distance from the lightning arrester if the steepness of the incident wave is high. By reducing the steepness the protective effect of lightning arresters is increased, particularly in an extended system.

The overhead earth wire over the protective zone eliminates the highest and steepest *surge voltages* which would result, in the absence of the earth wire, from direct strokes to the phase conductors in close promixity to the station. Surge voltages produced outside the protective zone are reduced by spark gaps or protective gaps installed at the line termination of the protective zone. In this case the earthing resistance exerts an important influence. Furthermore, these overvoltages are attenuated before they reach the station, particularly because of corona losses. The efficacy of this effect is determined by the length of the protective zone.

The *surge current* which impinges on the lightning arresters or condensors in a substation as a result of a direct stroke to the line outside the protective zone is limited initially by the surge impedance of the line. Later however the current is increased by successive reflections. Its value depends principally on the total inductance of the line between the point struck and the substation and furthermore on the length of the protective zone.

In this connection it is advisable to apply the *general principles* governing the installation of overhead earth wires for the protection of very high voltage lines, viz.

I. Arrangement of phase conductors and earth wires in such a manner that the latter intercept direct strokes;

II. Selection of the insulation and earthing arrangements so as to prevent back flashover of the insulators;

III. Spacing of phase conductors and earth wires so as to prevent back flashover between them.

These points do not, however, cover the whole subject of station protection. The following considerations offer a contribution to clarifying the *surge phenomena* arising under different conditions and to solving the following *problems*:—

1. Are there, beyond the principle II any additional precautions advisable with respect to the earthing system and is it advantageous

or dangerous to connect the earth wire directly to the earthing system of the station?

2. What are the consequences of a back flashover in the protective zone, apart from the resulting short-circuit, with respect to the station protection?

3. Does a large coupling factor k produce dangerous induced overvoltages on the phase conductors and should a greater number of earth wires be avoided for that reason?

2. FUNDAMENTAL SURGE EQUATIONS

In applying the general equations for multi-conductor systems it suffices to confine these to the approximate formulae applying to waves of uniforme velocity, neglecting complications due to corona effects and earth resistivity. Application of the theory of waves of different velocities would be more laborious without, however, reproducing exactly the two phenomena mentioned. In addition, results due to differences in the velocities of the various component waves become manifest only at great distances from the point of impact whereas the protective zone is comparatively short.

A practical simplification results from treating the *group of* phase *conductors* A, B, C as a single resulting conductor M and the group of earth wires E, F as a single conductor N. This is permissible if the conductors of one group are subjected to approximately equal voltages in the problems to be considered; this implies that the case of back flashover to a single phase conductor must be excluded. If the group M comprises m phase conductors and the group N comprises n earth wires the impedances of the resulting waves are given by

$$\left.\begin{aligned} Z_{MM} &= \frac{1}{m} Z_{AA} + \frac{m-1}{m} Z_{AB}, \\ Z_{NN} &= \frac{1}{n} Z_{EE} + \frac{n-1}{m} Z_{EF}, \\ Z_{MN} &= Z_{AE}. \end{aligned}\right\} \quad (1)$$

Two identical indices correspond to the self impedance of a conductor or of a group while two different indices refer to the mutual impedance between two conductors or two groups.

The *voltage and current surges* of groups M and N propagated in both direction which are designated by the index 1 on the right and 2

on the left are described by the following four *fundamental equations*:

$$\left.\begin{aligned} u_{M1} &= Z_{MM}\, i_{M1} + Z_{MN}\, i_{N1}, \\ u_{N1} &= Z_{MN}\, i_{M1} + Z_{NN}\, i_{N1} \\ u_{M2} &= -Z_{MM}\, i_{M2} - Z_{MN}\, i_{N2}, \\ u_{N2} &= -Z_{MN}\, i_{M2} - Z_{NN}\, i_{N2}. \end{aligned}\right\} \quad (2)$$

These equations express the component waves and do not determine directly the phenomena resulting from a superposition of several reflected waves.

In what follows repeated use is made of the *coupling coefficient K*. This is the ratio between the voltage induced in the phase conductors M and the inducing voltage on the earth wires N. It is thus given by

$$k = \frac{Z_{MN}}{Z_{NN}}. \quad (3)$$

In the various cases examined below reflections occur at the points at which group N is earthed and at the termination of the protective zone. In the formulae the *reflection coefficient* α_N is introduced for group N. This is the ratio between the resulting surge voltage at the point considered to the incident surge voltage. Assuming an intermediate earth point with a resistance R this factor becomes

$$\alpha_N = \frac{2R}{Z_{NN} + 2R}. \quad (4)$$

and for the termination of the protective zone where the earthing resistance of the group N is R_N or R it becomes respectively

$$\alpha = \frac{2R_N}{Z_{NN} + R_N} \quad \text{or} \quad \alpha_N = \frac{2R}{Z_{NN} + R}. \quad (5)$$

3. STROKE TO THE EARTH WIRE AT THE STATION TERMINATION

Examination of the case of a direct stroke to the earth wire in the immediate proximity of the station must determine the surge voltages which impinge on the station and the stresses to which the protecting lightning arresters are subjected. The results differ according to whether the earth wire is connected to the earthing system of the station or whether it is earthed separately. It is of course assumed that all metallic masses and the lightning arresters are bonded to the earthing system of the station.

A. **Separate earth connections.**—Under the conditions reproduced schematically in figure 1 the earthing resistance of the earth

wire N at the station termination may have a resistance R_N. The lightning arresters on the three phases and the earthing system of the station are characterized by a resulting resistance R_M. The lightning current is i_0 and the voltages and currents at the line terminations u_M, u_N, i_M, i_N. The only waves to be considered are u_{M2}, u_{N2}, i_{M2}, i_{N2} which are propagated towards the left. Applying the basic formulae (2) and adding further equations which express the electrical conditions at the line termination one obtains fairly complex general expressions for the voltages and currents at the line termination. From these, simplified equations are derived for particular interesting cases.

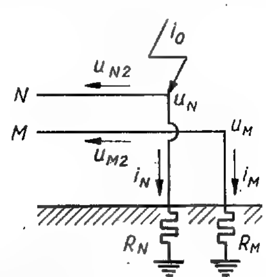

FIG. 1.—Lightning stroke to the earth wire N at the terminal station. Case of separate earthing systems.

a) The case of a comparatively very small resistance R_N and a comparatively very large resistance R_M as compared with the surge impedances Z_{MM}, Z_{NN}, Z_{MN} applies *before the sparkover of the lightning arrester gaps* in the station of when the arrester does not operate. This leads to the simplified expressions

$$u_N \approx R_N\, i_0, \tag{6}$$
$$u_M \approx kR_N\, i_0. \tag{7}$$

The coupling factor k has here the same significance as in the case of a direct stroke at a distance from the line termination when the earth wire influences the phase conductors in both directions from the point struck.

b) The case of two very small resistances R_N, R_M as compared with the surge impedances Z_{MM}, Z_{NN}, Z_{MN} applies often *during the lightning arrester discharge*. This leads to the approximate equations

$$u_N \approx R_N\, i_0, \tag{8}$$
$$u_M \approx k\,\frac{R_M}{Z_{MM}}\,R_N\, i_0, \tag{9}$$
$$i_M \approx k\,\frac{R_N}{Z_{MM}}\, i_0. \tag{10}$$

Numerical example. For $i_{0\max} = 150$ kA, $\left(\frac{di_0}{dt}\right)_{\max} = 50$ kA/μs, $k = 0.4$ (two earth wires), $Z_{MM} = 200\ \Omega$ and for

R_N	2	5	10	20 Ω

one obtains before sparkover of the lightning arrester gaps

$u_{M\max}$	120	300	600	1,200 kV
$\left(\frac{du_M}{dt}\right)_{\max}$	40	100	200	400 kV/μs

and after sparkover

$i_{M\max}$	0,6	1,5	3	6 kA.

The high values for u_M before operation of the lightning arresters indicate that sparkover of the arrester gaps is mots likely, particularly on medium-voltage systems. The rate of rise of u_M before sparkover is comparatively high and this is disadvantageous for the insulation co-ordination in the station. The resulting values for i_M during the operation of the lightning arresters are quite tolerable considering the discharge capacity of these devices.

B. **Effect of inductive voltages.**—The results obtained under *A* show that it is advisable to reduce the resistance R_N. However, it must be realized that in addition to the voltage drop in the earthing electrode *other voltage components* can play an important part. These are inductive voltages produced by the surge current discharged through the tower or through the earth lead and indirect surges induced by the lightning channel.

As a first approximation the voltage drop $R_N i_0$ in equations (6) ... (10) can be replaced by the *resulting voltage*

$$u_N \approx R_N\, i_0 + L_N \frac{di_0}{dt} \tag{11}$$

where L_N represents the inductance of the loop formed by the group N and earth. For a calculation of the crest values $u_{N\max}$ it is advantageous to adopt for the current i_0 a sinusoidal wavefront as shown in figure 2. This leads readily to

$$u_{N\max} \approx \frac{1}{2} R_N\, i_{0\max} + \sqrt{\frac{1}{4} R_N^2\, i_{0\max}^2 + L_N^2 \left(\frac{di_0}{dt}\right)_{\max}^2}\,. \tag{12}$$

In what follows the inductive and induced components are omitted in order to avoid a complication of the resulting equations. However, it is necessary to remember the possible effect of these components.

C. **Case of bonded earthing systems.**—By connecting the earth wire to the earthing system of the station a satisfactory earthing arrangement can be obtained economically. Even if no full benefit can be obtained from a large and extended earthing system on account

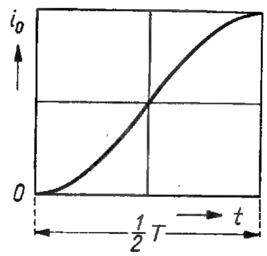

Fig. 2.—Sinusoidal wave front of the lightning current.

of its inductance, effective protective use is at least made of that part adjacent to the line termination. The resistance R in figure 3 is such an earthing resistance and this is often greater than the normal-frequency resistance of the whole system. The resistance R_M in this figure represents the lightning arresters. The lightning current is designat-

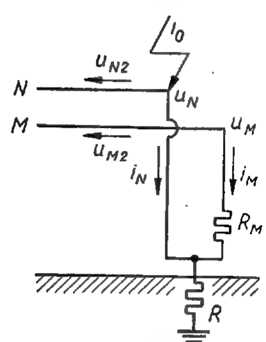

Fig. 3.—Lightning stroke to the earth wire N at the terminal station. Case of interconnected earthing systems.

ed by i_0, the surges at the station termination by u_M, u_N, i_M, i_N and the reflected surges by u_{M2}, u_{N2}, i_{M2}, i_{N2}. The basic equations (2) and a series of additional equations expressing the electrical conditions at the line termination lead to complicated general formulae for the

resulting voltages and currents. Simplified expressions can be developed for two special cases.

a) The case where the resistance R is comparatively very small and the resistance R_M very large as compared with the impedances Z_{MM}, Z_{NN}, Z_{MN} applies *before the sparkover of the lightning arrester gaps* or when the arrester does not operate. This leads to the simplified expressions

$$u_N \approx Ri_0, \tag{13}$$

$$u_M \approx kRi_0, \tag{14}$$

$$u_M - u_N \approx -(1-k)\, Ri_0. \tag{15}$$

The voltage $(u_M - u_N)$ determines the sparkover of the lightning arrester gaps while the negative sign indicates the occurrence of a back flashover.

b) The case where the two resistances R, R_M are very small compared with the impedances Z_{MM}, Z_{NN}, Z_{MN} may apply *during the operation of the lightning arresters.* This leads to the following simplified equations

$$u_N \approx u_M \approx Ri_0, \tag{16}$$

$$u_M - u_N \approx -(1-k)\frac{R_M}{Z_{MM}} Ri_0, \tag{17}$$

$$i_M \approx -(1-k)\frac{R}{Z_{MM}}\, i_0. \tag{18}$$

Numerical example. Whit the numerical values as under A for

R	0,5	1	2	5 Ω

the results before sparkover of the lightning arrester gaps

$(u_M - u_N)_{max}$	—45	—90	—180	—450 kV
$\left[\frac{d(u_M - u_N)}{dt}\right]_{max}$	—15	—30	— 60	—150 kV/μs

and after sparkover

$i_{M max}$	—0.225	—0.45	—0.9	—2.25 kA

For a small value of R the rate of rise of the voltage $(u_M - u_N)$ before sparkover is comparatively small although the factor $(1 - k)$ in expression (15) is often larger than the coefficient k in expression (7). It may even happen that the crest value of $(u_M - u_N)$ is too small to cause a back flashover of the lightning arresters. When sparkover occurs the crest value of the current i_M is much smaller than in case A with separate earth connections and this condition does not constitute any danger for the lightning arresters. However, for small currents i_M the resistance R_M may give comparatively high values in contrast

to the basic equations (16) ... (18). This part of these considerations is therefore not very precise.

Summarizing, it may be said that interconnection of the earthing systems produces advantages without introducing dangers to insulation and lightning arresters.

4. TRANSMISSION OF SURGES PAST POINTS AT WHICH THE EARTH WIRE IS EARTHED

In a discussion of the phenomena arising during the transmission of waves past earthing points along the protective zone the following *two problems* must be considered:—

1. In the case of a stroke to a phase conductor beyond the earth wire, are there any other factors which assist in the attenuation of transmitted waves apart from the earthing arrangement near the point struck and the corona losses along the protective zone;

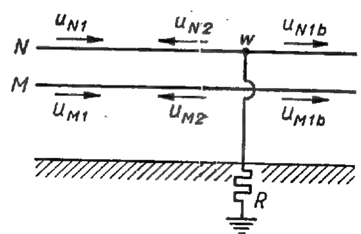

FIG. 4.—Transmission of surge waves past an earthing point of the earth wire N.

2. In the case of a stroke to the earth wire, what factors may cause a reduction of the surge voltages as they are propagated towards the station and is the risk from back flashovers reduced in consequence?

A. **Transmission past a single earth point.**—Starting from the electrical conditions shown in figure 4 the waves u_{N1}, i_{N1}, u_{M1}, i_{M1} arrive from the point struck at the branching point w where the earth wire N is earthed through the resistances R. The waves u_{N2}, i_{N2}, u_{M2}, i_{M2} are reflected whereas the waves u_{N1b}, i_{N1b}, u_{M1b}, i_{M1b} are transmitted.

Using equations (2) and the equations determining the voltages and currents at the point w the following *general equations* are obtained for the transmitted waves

$$u_{N1b} = \alpha_A \, u_{N1}, \tag{19}$$

$$u_{M1b} = u_{M1} - \frac{Z_{MN}}{Z_{NN} + 2R} \, u_{N1}. \tag{20}$$

For $R \leqslant Z_{NV}$ the second expression can be simplified to

$$u_{M1b} \approx u_{M1} - ku_{N1}. \qquad (21)$$

it is of interest to examine three particular cases.

a) The cases where $u_{M1} = Ku_{N1}$ applies after a stroke to the earth wire and *without back flashover*. Expression (21) is then no longer sufficiently exact. Utilizing equation (20) one finds

$$u_{M1b} \approx \alpha_N \, u_{M1}. \qquad (22)$$

According to this equation the transmitted waves on the phase conductors are greatly reduced as a result of the reflection coefficient of the earth wire N. Equally the rate of rise of the transmitted surges is reduced and this is advantageous for the insulation co-ordination within the station.

b) The case $u_{M1} = u_{N1}$ may arise as the result of *back flashovers* after a lightning stroke to the earth wire. This leads to the expression

$$u_{M1b} \approx (1 - K) \, u_{M1}. \qquad (23)$$

Which shows that the transmitted wave u_{M1b} is considerably reduced but not to the same extent as in the preceding case according to equation (22). The wave u_{M1b} is thus much higher than the wave u_{N1b} and equation (23) can no longer be applied to a subsequent reflection at another earthed point.

c) The case $u_{M1} \geqslant u_{N1}$ ensues at *subsequent earthing points* after case *b*) or when surges are propagated from the non-shielded part of the overhead line. From equation (21) this leads to

$$u_{M1b} \approx u_{M1}. \qquad (24)$$

which indicates that no noticable reduction occurs in the surge voltages propagated along the phase conductors.

B. **Transmission past several earth points.**—The considerations under "A" have shown that the surges voltages on the phase conductors are greatly reduced by reflections at successive earthing points of the earth wire in the case *a*) if *lightning strikes the earth wire without producting back flashover*. Transmission past one earth point reduces the surge voltages both on the earth wires and on the phase conductors in accordance with the reflection coefficient α_N.

After passing w equal earthing points, $w_b \dots w_h$ in figure 5, the transmitted waves are described initially by the equations

$$u_{N1h} = \alpha_N^w u_{N1}, \tag{25}$$
$$u_{M1h} = \alpha_N^w u_{M1}. \tag{26}$$

These are however merely the *first transmitted waves*.

As the span lengths are limited these *waves* are quickly *reflected*. The first transmitted surges are therefore followed by subsequent reflections by which the rate of rise of the surge voltage in the station is increased. The resulting wave trains approach gradually the surge voltages which resulted in the case of transmission past a single earthing point whith the resistance $\frac{1}{w} R$ which would be characterized by a transition coefficient $\frac{1}{w} \alpha_N$.

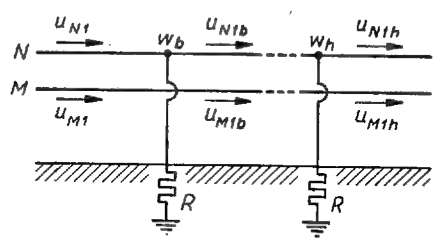

FIG. 5.—Transmission of surge waves past several earthing points $w_b \dots w_h$ of the earth wire N.

Numerical example. If $Z_{NN} = 300\ \Omega$, $R = 10\ \Omega$, $\alpha_N = 0{,}063$ one finds for

w	1	2	3	4
the coefficient for the first transmitted wave				
α_N^W	0.063	0.004	0.00025	0.000016
and the final coefficient resulting from the train of reflected waves				
$\frac{1}{w} \alpha_N$	0.063	0.031	0.021	0.016

A comparison of the values α_N^W and $\frac{1}{w} \alpha_N$ shows that the efficacy of several earthing points is reduced in the course of successive reflections, but it always remains high. The surge voltages arriving at the station are not discussed here as they would be intermediate between the values corresponding to the coefficients α_N^W and $\frac{1}{w} \alpha_N$.

5. REFLECTION OF WAVES AT THE TERMINAL STATION

As in section 3, the case of separate earths at the station is examined first and this is followed by the case of interconnected earths.

A. **Case of separate earthing systems.**—Under the conditions represented by figure 6 the incident waves are u_{N1}, i_{N1}, u_{M1}, u_{M1}, the waves reflected at the terminal station u_{N2}, i_{N2}, u_{M2}, i_{M2}, the resulting voltage surges u_N, u_M while the currents i_N, i_M are discharged

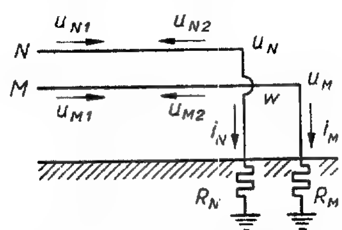

FIG. 6.—Reflection of surge waves at the terminal station of a protective zone. Case of separate earthing systems.

through the resistances R_N, R_M. The resistance R_M represents not only the earthing resistance but also that of the lightning arresters. Applying the basic equations (2) and additional equations describing the conditions at the terminal station fairly complicated equations are derived for the resulting voltages and currents. However it suffices to base conclusions on simplified relations applying to given conditions.

The phenomena *before sparkover of the lightning arresters* are of primary importance in view of the significance of the rate of rise of the surge voltages on the insulation co-ordination in the station. This case is described by a resistance R_N which is comparatively very small and a resistance R_M which is very high as compared with the impedances Z_{MM}, Z_{NN}, Z_{MN}. Simplifying the general equations the following approximate expressions result

$$u_N \approx \alpha_N u_{N1}, \tag{27}$$

$$u_M \approx 2u_{M1} - 2Ku_{N1}. \tag{28}$$

We now turn to the examination of *three special cases* as in section 4 A.

a) In the case $u_{M1} = ku_{N1}$ equation (28) is not sufficiently exact. From the general relations one finds

$$u_M \gtrapprox \alpha_N u_{M1}. \quad (29)$$

This indicates a very effective reduction of the surge voltage and also a diminuation of the rate of rise and this is advantageous for the insulation co-ordination in the station.

b) In the case $u_{M1} = u_{N1}$ one finds

$$u_M \gtrapprox 2\,(1 - K)\,u_{M1}. \quad (30)$$

The attenuating effect of the earth wire is therefore small compared with case *a*).

c) In the case $u_{M1} = -u_{N1}$ one obtains simply

$$u_M \gtrapprox 2u_{M1}. \quad (31)$$

The reflection at the open end of the phase conductors *M* develops in this case in the same manner as on a line without earth wire.

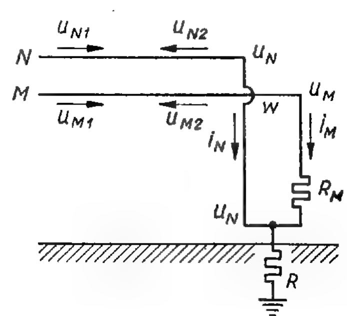

FIG. 7.—Reflection of waves at the terminal station of a protective zone. Case of interconnected earthing systems.

However in practice a station constitutes never an open line end. Instead, attenuating factors enter into play such as the station capacitances and often additional lines and windings.

B. **Case of interconnected earthing systems.**—Considering the electrical conditions represented in figure 7 and adopting the same notation as above equations (2) and additional equations are applied expressing the state of the line termination. This leads to fairly complicated equations for the voltages and currents.

As in Section A it may suffice to examine the phenomena *preceding the sparkover of the lightning arresters* by assuming that the resistance R is very small and the resistance R_M very large compared with the impedances Z_{MM}, Z_{NN}, Z_{MN}. Simplifying the general equations one finds

$$u_N \gtrapprox \alpha_N u_{N1}, \qquad (32)$$

$$u_M \gtrapprox 2u_{M1} - 2ku_{N1}, \qquad (33)$$

$$u_M - u_N \gtrapprox 2u_{M1} - (2k + \alpha_N)\, u_{N1}. \qquad (34)$$

We may confine ourselves to *three particular cases* and especially to the voltage $(u_M - u_N)$ which develops across the terminals of the lightning arrester and adjacent insulation.

a) For the case $u_{M1} = ku_{N1}$ equations (33) and (34) are not sufficiently accurate. Starting from the general equations one finds

$$u_M - u_N \gtrapprox -\alpha_N \frac{1-k}{k} u_{M1}. \qquad (35)$$

A coefficient α_N which is smaller than for the case of separate earthing systems leads in this case to a greater reduction of the surge voltages and a more effective attenuation of the rate of voltage rise although the factor $\frac{1-k}{k}$ may exceed unity.

b) In the case $u_{M1} = u_{N1}$ equation (34) gives

$$u_M - u_N \gtrapprox (2 - 2k - \alpha_N)\, u_{M1}. \qquad (38)$$

This indicates a comparatively small effect of the earth wire.

c) In the case $u_{M1} \geqslant u_{N1}$ one finds simply

$$u_M - u_N \gtrapprox 2u_{M1},$$

as though the earth wire did not exist.

6. CONCLUSIONS

1. The efficacy of an earth wire over the protective zone of a station is excellent provided the three general principles for such an earth wire (I, II and III of Section I) are fulfilled. In particular, back flashover must be avoided not only so as to prevent a short circuit, but also so that the station may benefit effectively from the presence of the earth wire.

2. In the case of a direct lightning stroke to the earth wire no high surge voltages are induced on the phase conductors in consequence of

the coupling coefficient k, except during the initial period and in immediate proximity of the point struck. Subsequently the surge voltages are attenuated very rapidly at the successive earthing points of the earth wire (Section 4, items *A-a* and *B-a*) and at the terminal station (Section 5, items *A-a* and *B-a*), provided back flashover does not occur.

3. The earthing of the earth wire must be particularly good at the terminal station. This effects a good attenuations of the waves propagated from the protective zone (Section 5) and greatly diminishes any possible danger arising from a stroke to the earth wire very close to the station (Section 3). An economic solution consists in the connection of the earth wire to the earthing system of the station and in an arrangement such that a large part of that earthing system is installed at the line termination. Such an interconnection improves the insulation co-ordination without subjecting lightning arresters to excessive stresses.

4. No arguments can be advanced against a high coupling factor k, i.e. against the installation of two or three earth wires. A high factor k does not produce dangerously steep surge voltages in the station particularly if the earth wire is connected to the earthing system of the station.

5. The advantages produced by an earth wire disappear quickly when back flashover occurs. The surge voltages propagated along the phase conductors towards the station (Section 4, items *A-b*, Section 5, items *A-b* and *B-b*) are reduced only moderately by earthing points along the protective zone and at the line termination of the station.

6. In the case of a lightning stroke to the line outside the protective zone the surge voltages propagated towards the station (Section 5, items *A-c* and *B-c*, Section 4, items *A-c*) are not greatly affected by the presence of the earth wire. In this case one must merely rely ont the principles enumerated in Section 1, viz. corona losses and installation of spark gaps or protective gaps at the line termination of the protective zone. It may be advisable to reduce the earthing resistance at this point below those of other earth points along the protective zone.

7. By neglecting inductive voltage drops results may be obtained which are too optimistic. An example of more complete and more accurate considerations is given in Section 3 (item *B*).

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113. — PROTECTION OF THE NEUTRAL POINT OF TRANSFORMERS

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SUMMARY.

When examining the problem of the protection of the neutral point of transformers by means of lightning arresters one must consider not only the overvoltages produced by atmospheric discharges between the winding and earth but also those which can arise across coils, layers and turns in that part of the winding which is adjacent to the neutral.

As will be seen in this report the stresses which can arise in the end part of the winding during the operation of a lightning arrester may, in certain unfavourable conditions, exceed those produced by a surge in the rest of the winding. The authors conclude from test results that the values of these stresses can be reduced by the installation at the neutral point of lightning arresters of reduced sparkover voltage and with an increased number of non-linear resistance elements.

REPORT

I. — INTRODUCTION.

It is generally agreed that in transformers with an isolated neutral or with a neutral earthed through an arc suppression coil it is the insulation of the neutral point which is subjected to the greatest

risk due to atmospheric discharges. Field investigations on high voltage systems in various countries have enabled the amplitudes of the surge voltages to be determined to which the neutral points of transformers are subjected during thunderstorms. The highest overvoltages occur at the transformer neutral when this is subjected to a three-phase surge, i. e. to three equal overvoltages on all three phases. In this case, considerable overvoltages can be produced at the neutral, reaching very often up to twice the maximum value of the terminal, voltage. If the winding is not overinsulated it cannot withstand such high stresses even if the terminal of the transformer is protected by a lightning arrester. Flashover of the neutral may so result. Such a flashover is equivalent to the application to the neutral of a very steep surge with a front duration of the order of 0.1 μs. The stresses of the insulation of coils, layers and turns produced by such a surge in the winding adjacent to the neutral point, superimposed on the stresses due to the incident surge, subject the end part of the winding to a considerable risk.

The necessity of protecting the neutral point of transformers is at present well recognized and accepted. There exist however divergent views on the best methods of protection.

Several different methods of protection have been suggested of which the following are the most important :

a. a lightning arrester connected to the neutral;
b. the neutral earthed through a capacitor;
c. the neutral earthed through an ohmic resistance;
d. the neutral earthed through an " impidor ";
e. electrostatic shielding of the end coils of the transformer winding.

In order to effect a sufficient reduction of the overvoltages of the neutral a protective capacitor must have a capacitance of several tens of μF. Such an device is expensive and its application for the protection of the neutral would not be economically acceptable.

According to reference [2] an ohmic resistance of about 2 000 Ω must be used for the protection of the neutral points of transformers up to 30 kV and several hundred kVA and a resistance of about 400 Ω for transformers up to 60 kV and exceeding 10 000 kVA. According to the authors these values were chosen with a fairly high margin of safety. However, the larger resistances require themselves a fairly high rating so as to withstand the short-circuit current to earth. Such a protection would not be economically justified.

The " impedors " are devices consisting of an arc suppression coil in parallel with a non-linear resistance and a capacitance. The non-linear resistance and the capacitor have the object to reduce the

surge stresses at the neutral point. The non-linear resistance which is connected directly to the neutral without a series sparkgap is subjected, in the case of a short circuit to earth, to a current of considerable amplitude and fairly long duration. Such resistances are difficult to design. The protection of the neutral point by such a device is therefore rather costly.

Electrostatic shielding of the coils adjacent to the neutral is only capable of reducing the longitudinal stresses near the transformer neutral, viz. the stresses across coils, layers and turns. On the radial stresses to earth they exert only a negligible effect. It thus follows that electrostatic shields on their own cannot satisfy the requirements of a protection of the transformer neutral.

From what we said above it follows that the methods enumerated under *b*, *c*, *d* and *e* do not produce satisfactory solutions of the problem of protecting the transformer neutral. For this reason they have not found a wide application. In what follows the problem of the protection of the transformer neutral by a lightning arrester will be examined.

II. — THE GENERAL PROBLEM OF THE PROTECTION OF THE NEUTRAL BY MEANS OF LIGHTNING ARRESTERS.

An investigation of this problem must deal with :

a. the protection of the insulation to earth;

b. the protection of the longitudinal insulation adjacent to the neutral.

In general, discussions of the problem of the stresses at the neutral point have been confined to the stresses produced between the insulation and earth. According to the best information available to the authors no results of measurements have been published of the longitudinal stresses produced in the winding near the neutral as the result of the operation of a lightning arrester. A careful examination of this problem leads to the conclusion that the insulation between coils near the neutral may be subjected, in certain cases, to much higher stresses than the other parts of the winding.

The present investigation aims at determining the values of these overvoltages as a function of the parameters of the lightning arrester and the conditions which lightning arresters intended for the protection of a transformer neutral have to satisfy.

test conditions as the coefficient α of the material used in the real lightning arrester has under practical operating conditions. For the tests with an impulse of 960 V a non-linear resistance material was used the coefficient of which, measured at reduced voltage (the current being below 1 A), was 0.26 whereas for the tests with the full surge voltage of 32.5 kV a material was chosen with α equals 0.20

III. — SURGE VOLTAGE MEASUREMENTS IN TRANSFORMER WINDINGS.

In order to determine the stresses to which the longitudinal insulation of a transformer is subjected if its neutral is protected by a lightning arrester the surge voltages have been measured which

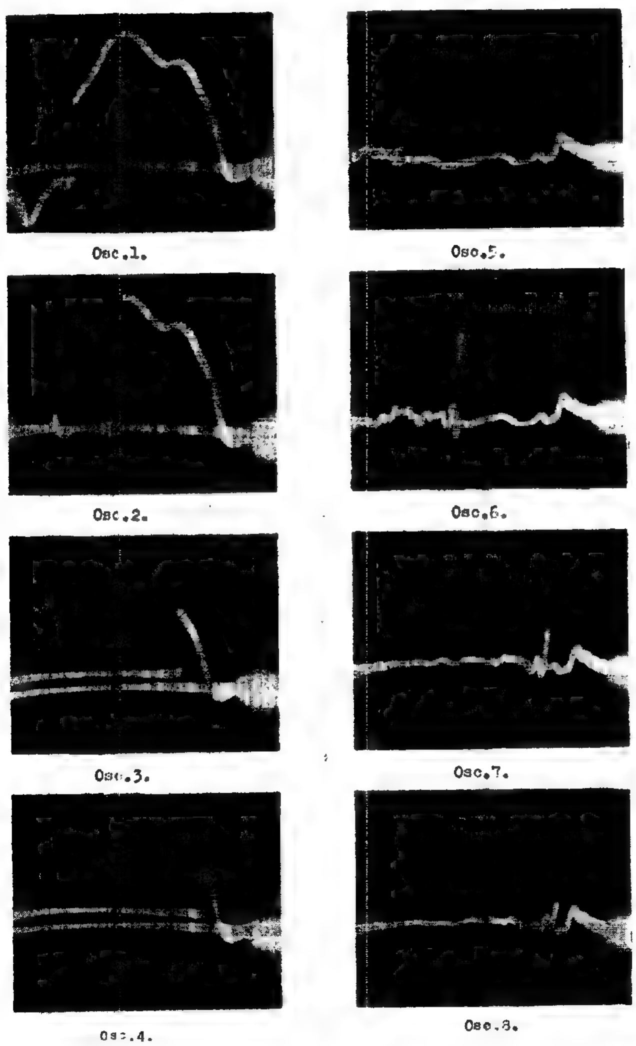


Fig. 1.

Osc. 1, 2, 3 and 4, voltage at the neutral as a function of the sparkover time lag of the model lightning arrester; 5, 6, 7 and 8, corresponding voltages across the last coil.

when measured with currents of the order of several tens of amperes. The value of the constant C of the non-linear resistance element was in both cases 2.6 kV/kAα.

IV. — TEST RESULTS.

The oscillograms 1, 2, 3 and 4 of figure 1 show the voltage at the transformer neutral, produced by a three phase surge voltage applied to the winding terminals. The shape of the test wave was 1/50 μs

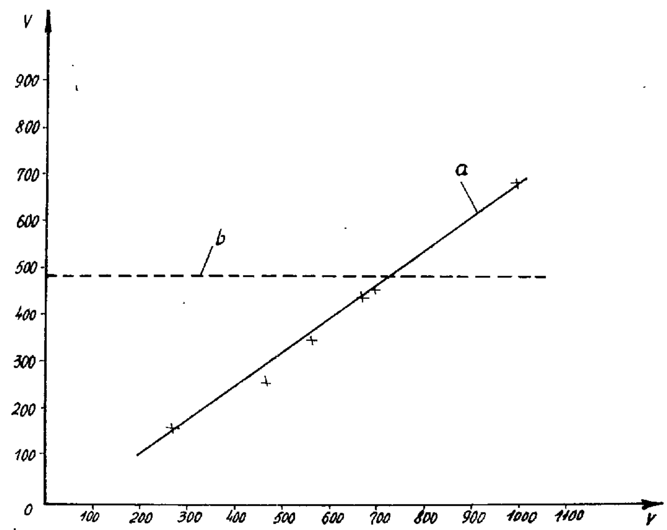


Fig. 2.

a. Variation of the voltage across the last coil as a function of the crest value of the " sparkover surge ", *b*. voltage across the entrance coil.

and its crest value 960 V. During these tests the neutral point was connected to earth through a lightning arrester in series with a thyratron. By alterning its grid potential the instant of firing of the thyratron can be adjusted. As can be seen from oscillogram 1, if sparkover occurs on the falling part of the voltage at the neutral the voltage drop across the non-linear resistance becomes negative. This means that if the sparkover of the lightning arrester occurs near the maximum or beyond the maximum on the falling part of

Fig. 4.

Osc. 1, 2, 3 and 4, voltages at the neutral with 1, 2, 3 and 6 non-linear resistance elements; 5, 6, 7 and 8, corresponding voltages across the last coil.

the voltage wave it may produce a higher " sparkover surge " (1) than the sparkover voltage and it may therefore cause overvoltages of considerable amplitude in the end part of the winding.

The oscillograms 5, 6, 7, 8 and 1, 2, 3 and 4 show that the over-voltages produced in the last coil as the result of the operation of the lightning arrester may attain a value high enough to become

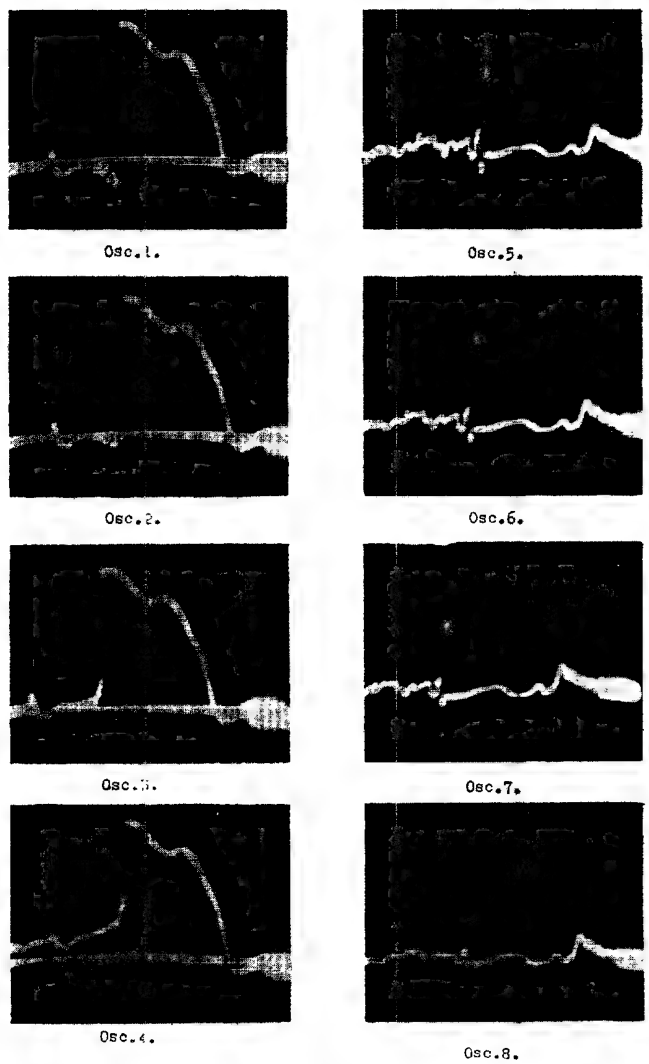


Fig. 5.

Osc. 1, 2, 3 and 4, voltages at the neutral recorded with 0, 1, 3 and 6 non-linear resistance elements; 5, 6, 7 and 8, corresponding voltages across the last coil.

surge as a function of the number of non-linear resistance elements. As can be seen these values decrease almost linearly with the number of elements. This leads to the conclusion that the discharge current through the lightning arrester remains almost unchanged despite the variation of the non-linear resistance. This is possible in the case where the value of the non-linear resistance of the lightning arrester is considerably lower than the surge impedance of the winding. One may say with reasonable approximation that the value of the transmitted wave which is equal to the potential drop across the

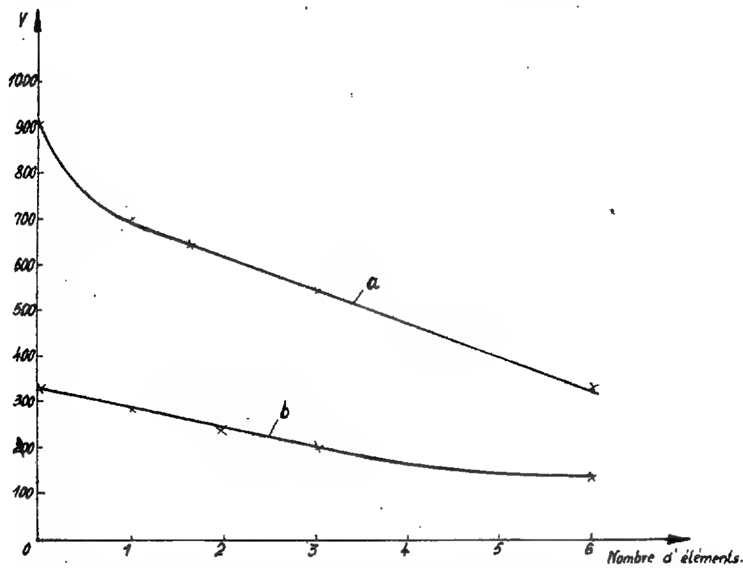


Fig. 6. — Variation of the voltage of the " sparkover surge " as a function of the number of non-linear resistance elements.
Curve *a*, with a sparkover voltage of 1 010 V (*fig.* 5);
Curve *b*, with a sparkover voltage of 650 V (*fig.* 4).

non-linear resistance is, in this case, directly proportional to the resistance of the lightning arrester and that for this reason the current remains practically unchanged.

The curves of figure 7 show the voltage across the last coil as a function of the number of non-linear resistance elements. It can be seen that the voltage decreases linearly as the number of elements increases.

The oscillogram of figure 3 shows the voltage produced across the entrance coil by a three-phase surge of 1/50 μs wave shape and 960 V crest value. The horizontal line in the diagram of figure 2 repre-

sents the maximum value of that voltage. It is evident that the sparkover voltage of the lightning arrester must be below 730 V, the value given by the point of intersection of the curves, if the voltage across the last coil is to remain below that of the entrance coil. When applying the scale ratio of the test model to the operational conditions this value of the limiting sparkover voltage becomes 90 kV,

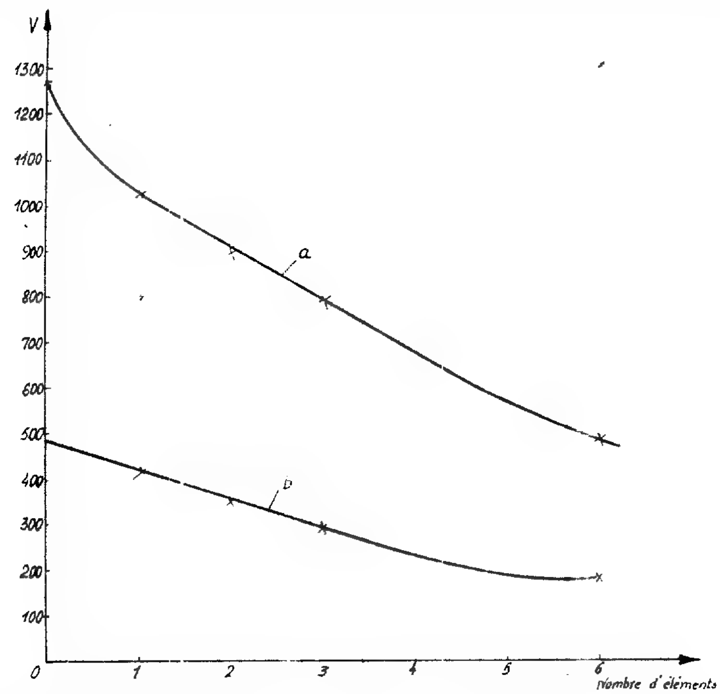
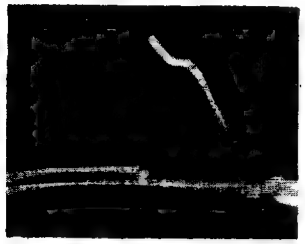


Fig. 7. — Variation of the voltage across the last coil as a function of the number of non-linear resistance elements.

Curve *a*, with a sparkover voltage of 1 010 V (*fig.* 5);
Curve *b*, with a sparkover voltage of 650 V (*fig.* 4).

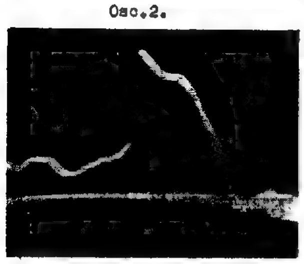
a value which corresponds to a 75 % lightning arrester. As has already been said one element of the model arrester corresponds to 35.5 elements of the actual arrester. If the residual voltage of the lightning arrester is allowed to reach its sparkover voltage, viz. 90 kV, it can be deduced from equation (1) that the maximum value of the discharge current must not exceed 750 A.

The oscillograms 1, 2, 3 and 4 of figure 8 show the voltage produced at the neutral by a three-phase surge of 1/150 μs. The neutral

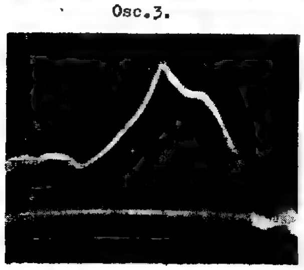


Osc.1.

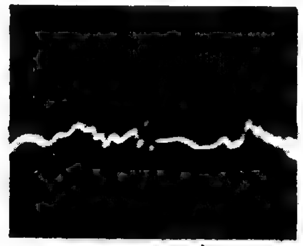
Osc.2.



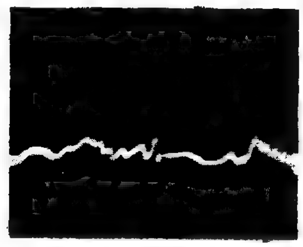
Osc.3.



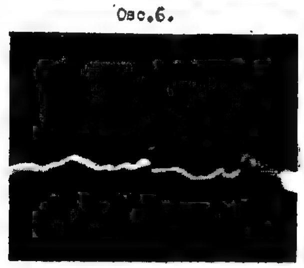
Osc.4.



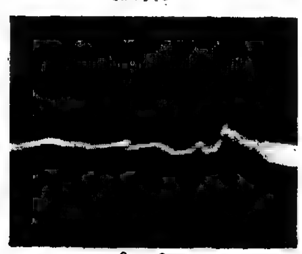
Osc.5.



Osc.6.



Osc.7.



Osc.8.

Fig. 8.

Osc. 1, 2, 3 and 4, voltage of the neutral with a constant resistance of 0.25 1, 4 and 12.8 kΩ; 5, 6, 7 and 8, corresponding voltages across the last coil.

point is earthed through a thyratron in series with a constant ohmic resistance which amounts respectively to 0.25, 1, 2, 4 and 12.8 kΩ. The oscillograms 5, 6, 7 and 8 show the corresponding values of the voltage across the last coil. As can be seen an increase of the resistance reduces the front steepness of the sparkover surge. This effect may be explained by the increase of the discharge time of the

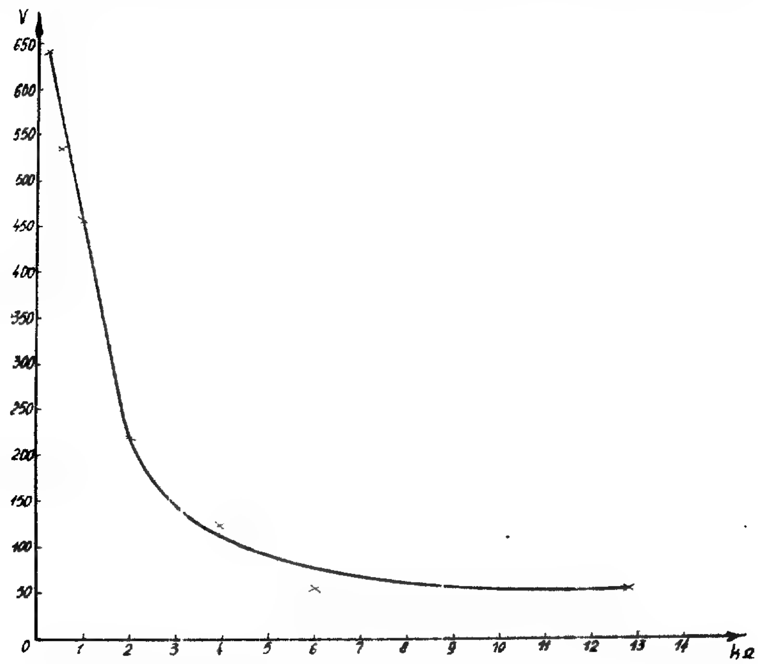


Fig. 9. — Variation of the voltage across the last coil as a function of the value of the constant resistance.

capacitance of the neutral point. In the case of a lightning arrester this effect is not so pronounced because the elements of the arrester have themselves a considerable capacitance. The relationship between the voltage across the last coil and that across the neutral resistance is shown by the curve of figure 9 from which it appears that for resistance values of about 2 kΩ the voltage decreases almost linearly with increasing resistance, for higher resistance values this increase occurs more slowly. This confirms the relationship established above between the value of the sparkover surge and that of the arrester resistance.

The curves of figure 10 show the maximum value of the voltage

across the last coil as a function of the crest value of the voltage of the sparkover wave. Curve *a* indicates the points measured with different values of the sparkover voltage and of the non-linear resistance at the neutral, curve *b* the points measured with different values of a constant resistance. For the case where the neutral is protected by a lightning arrester it can be seen from curve *a* that the voltage value across the last coil is directly proportional to the

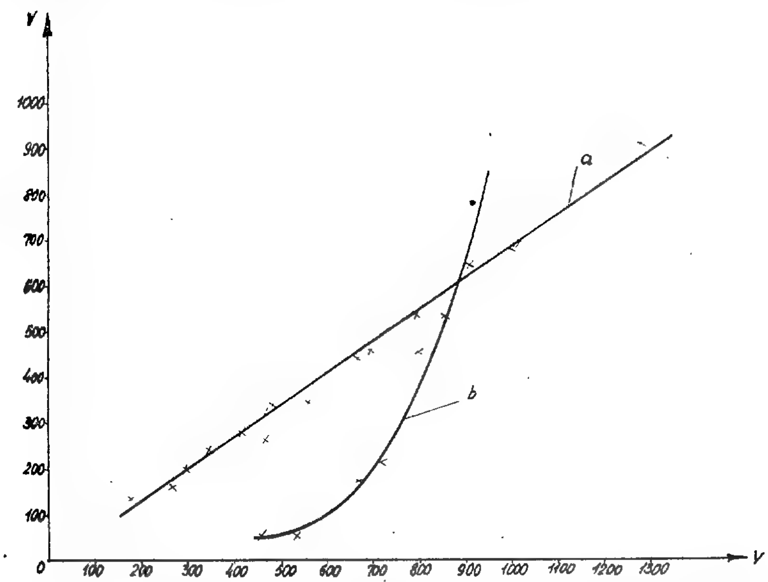


Fig. 10. — Variation of the voltage across the last coil as a function of the voltage of the " sparkover surge ".
Curve *a*, with non-linear resistance at the neutral;
Curve *b*, with constant resistance at the neutral.

value of the sparkover surge and is independent of the waveshape of the incident surge and also of the time lag to sparkover and the value of the non-linear resistance. If the non-linear resistances are replaced by constant resistances the above relation is modified in that the curve which represents this relation decreases almost linearly for small resistance values and more slowly for larger values.

The diagram of figure 11 shows the value of the voltage across the last coil as a function of the number of non-linear resistance elements. The measurements were carried out with a three-phase surge of 1/50 μs and 32.5 kV. Taking into account that the time to half value of the voltage measured was very short, of the order

of 0.5 μs or less, and that this voltage was measured by means of a sphere gap no great accuracy can be expected. The test values can therefore merely be regarded as indicative.

With due regard to the scale the 30 kV lightning arrester was replaced by a sphere gap adjusted to a distance corresponding to a

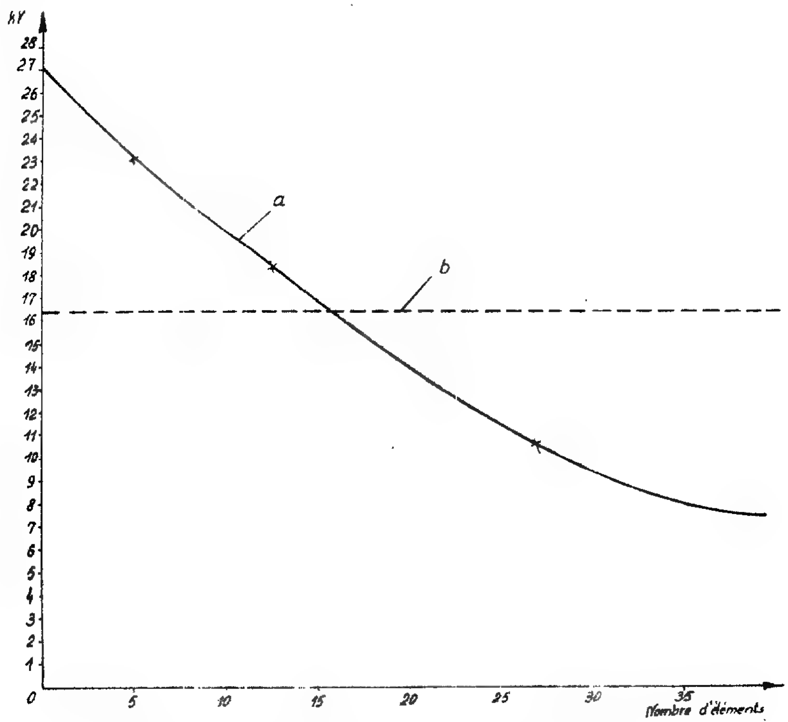


Fig. 11.

Curve *a*, voltage across the last coil as a function of the number of non-linear resistance elements.
Curve *b*, voltage across the entrance coil.

sparkover voltage of 32.5 kV and a non-linear resistance comprising 10 elements. The line on the right of the diagram of figure 11 shows the value of the voltage across the entrance coil. The point at which the curves intersect indicates that the voltage across the last coil equals that across the entrance coil if a lightning arrester of 15 elements is connected to the transformer neutral.

Figure 12 shows the voltage recorded during tests across the non-linear resistance.

Figure 13 shows a calibrating oscillogram with the aid of which the duration of the voltages recorded on oscillograms in figures 1, 3, 4, 5 and 8 can be determined.

Fig. 12. — Oscillogram of the voltage across the non-linear resistance.

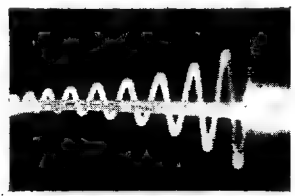


Fig. 13. — Calibrating oscillogram. Duration of oscillation, 18 μs.

Furthermore, measurements have been made of the surge voltages procuded by a three-phase surge in the winding of a 110 kV transformer of 31.5 MVA with electrostatic shields on several entrance coils. The neutral point was protected by a model lightning arrester of normal construction for 65 % of the nominal voltage and 1.5 kA discharge capacity. After the sparkover of the arrester the voltage across the last oil slot, between the last two coils, exceeded by 10 % that across the first slot, between the first two coils.

V. — THEORETICAL ANALYSIS.

The theoretical interpretation of the phenomena produced at the neutral point by the sparkover of a lightning arrester is fairly difficult in view of the fact that the surge impedance of the winding is a function of time and that the current in the winding is out-of-phase with the voltage. However, an approximate consideration of these phenomena may proceed from the assumption that the surge impedance remains constant and that the current is in phase with the voltage at the neutral.

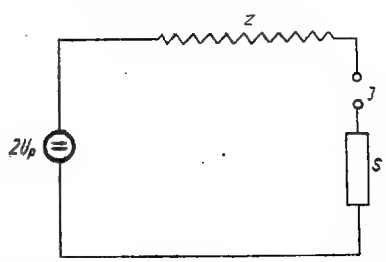


Fig. 14. — Equivalent circuit of a transformer with a lightning arrester at the neutral.

Z, surge impedance of the transformer; *S*, non-linear resistance of the lightning arrester; *J*, series gap of the lightning arrester.

Figure 14 shows an equivalent circuit by which the value of the sparkover surge can be determined. It may be assumed that sparkover of the lightning arrester occurs at the instant when the

voltage at its terminals reaches the value of the impulse sparover U_z. The voltage of the incident surge U_p becomes then

(5) $$U_p = \frac{U_z}{a},$$

where $\frac{1}{a}$ represents the reflection coefficient of the incident wave at the neutral point.

Assuming zero sparkover time lag there follows

(6) $$2U_p = iZ + U_s,$$

where

U_s is the voltage drop across the non-linear resistance immediately after sparkover of the lightning arrester;
Z, the surge impedance of the winding;
i the discharge current.

The factor k designates the ratio of the crest value of the sparkover voltage ($U_z - U_s$) and the value of the sparkover voltage

(7) $$k = \frac{U_z - U_s}{U_z}.$$

Adopting for the non-linear resistance the relation (1) and substituting (1) and (5) in (6) one obtains

(8) $$k = 1 - \frac{\left(2\frac{1}{a} + k - 1\right)^{\alpha} C}{Z U_z^{1-\alpha}}.$$

The expression $\left(2\frac{1}{a} + k - 1\right)^{\alpha}$ for the values of k, a and α encountered in practice is very nearly equal unity. From equation (8) it therefore follows that k is directly proportional to C, viz. to the number of non-linear resistance elements and inversely proportional to the surge impedance Z to the power α and to the value of the sparkover voltage to the power $1 - \alpha$.

The theoretical results thus confirm the test results.

VI. — DISCUSSION.

The measurements performed with the 30 kV transformer of 100 kVA and the 110 kV transformer of 31.5 MVA have shown that in the case where the neutral point is protected by a 100 % lightning

arrester the value of the voltage across the last coils exceeds the value of the voltage in the remainder of the winding. The situation is improved if a lightning arrester is used in which the sparkover voltage is reduced and in which the number of non-linear resistance elements is increased. As has been shown by a large number of tests the discharge current through the lightning arrester at the neutral is very little increased — by several units for several tens of amperes — and the residual voltage does not exceed the value of the protective level, provided the number of resistance elements of the arrester is increased several times. If the same material is used for the lightning arrester intended for the protection of the neutral point as in the normal arrester the number of non-linear resistance elements may be increased considerably. The resistance of the arrester under surge conditions is then increased and it becomes possible, therefore, to reduce its sparkover voltage.

The results obtained apply, strictly speaking, only to the type of transformer on which the tests were made but similar phenomena would undoubtedly occur in transformers of different voltage and power. The problem of protecting the neutral point is of particular importance for transformers in which effective measures have been applied to reduce considerably the stresses across the entrance coils, e. g. transformers with electrostatic shields on the entrance coils. The dimensions of the transformer insulation are then determined by the stresses which may arise in the end coils after sparkover of a normal type of lightning arrester. Under these conditions, application of an arrester of normal construction, even for 65 %, may produce stresses in the end coils which exceed appreciably those in the rest of the winding. It becomes then necessary to install at the neutral a lightning arrester for which the number of non-linear resistance elements and the sparkover voltage are so chosen as to ensure that the longitudinal stresses near the neutral point do not exceed those produced at other parts of the windings. It would even be justified to reduce the stresses of the neutral by means of similar devices as employed at the line end, e. g. by means of electrostatic shields for the end coils of the winding.

VII. — CONCLUSIONS.

1. The stresses produced by the sparkover of a lightning arrester at a transformer neutral may endanger the insulation of the end coil of the winding.

2. The most suitable arresters for the protection of the neutral points are those with :

a. sufficiently low sparkover voltage;

b. sufficiently large number of non-linear resistance elements.

3. The voltages produced across the end coils of the winding are almost directly proportional to the crest value of the " sparkover surge ".

4. In certain cases the crest value of the " sparkover surge " may exceed the value of the sparkover voltage of the arrester.

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LARGE HYDROELECTRIC GENERATORS OF THE SOVIET UNION

by

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M. J. Kaplan, P. M. Ipatov

1. INTRODUCTION

(progress in the construction of hydroelectric generators in the Soviet Union)

The construction of hydroelectric generators in the Soviet Union has immensely developed in the past 30 years. The first units that had a capacity of 8.7 *MVA* and a speed of 75 r.p.m. were constructed for the first hydroelectric development in the electrification of our country, the Volkhov hydroelectric station. At the present time, units with a capacity of 123.5 *MVA* and a speed of 68.2 r.p.m. are being constructed for the Volga stations, and super units with a capacity of 200 *MVA* are being designed for developments on the rivers of Siberia.

The main source of the immense hydro potential in the European as well as in the Siberian parts of the Soviet Union lies in the large-level rivers of the country. Many hydroelectric stations equipped with generators and turbines of Soviet manufacture have been and are now being constructed on these rivers that have large stream flow and small heads.

The factories of the Soviet Union manufacture tens of types of large hydrogenerators that have speeds ranging from 62.5 to 750 r.p.m. including 123.5-*MVA* generators with a speed of 68.2 r.p.m. designed for the Kuibyshev hydroelectric development.

Generators with very low speeds from 62.5 to 83.3 r.p.m. and ratings up to 100 *MVA* per unit are in most cases installed in the large hydroelectric stations of the Soviet Union. Units with speeds from 100 to 375 r.p.m. and capacities of 85—66 *MVA* are considerably less used. High-capacity slow-speed units lead to the construction of very large-sized machines. Machines of this type that are being built at the present time in the U.S.S.R. are larger than those of any other country.

The 68,750-*KVA*, 62.5-r.p.m. units operating since 1940 in hydroelectric stations on the Volga were for several years the largest units of their kind in the world. Even larger 71,500-*KVA* units are at present under construction. Finally, several of a large quantity of super-sized generators have already been built for the hydroelectric developments in the Kuibyshev and Stalingrad areas, which are being constructed in accordance with the five-year plan.

The essential data of the largest of these units are given in table 1.

TABLE 1

Capacity *P*, *KVA*	Speed, r.p.m.	*KVA* per r.p.m.	Outside diameter of frame, mm	Load on thrust bearing, tons
68,750	62.5	1,130	14,400	2,100
103,500	83.3	1,080	13,100	1,000
71,500	62.5	1,140	15,500	2,000
123,500	62.2	1,820	17,400	3,400

As seen from table 1, the large low-speed hydroelectric generators manufactured in the Soviet Union have the following features: large dimensions, heavy loads on the thrust bearing caused by the heavy weight of the rotating parts, and large water pressures on the turbine wheel.

2. PARAMETERS OF THE HYDROELECTRIC GENERATOR AND ESSENTIAL TECHNICAL DATA

The essential parameters determining the operation of a hydroelectric generator under steady state and transient conditions are as follows: the synchronous, transient and sub-transient reactances, the inertia constant, the time constants of the generator windings, and the efficiency.

Typical generator parameters for machines of various capacities and speeds are given in table 2.

TABLE 2

Generator capacity, *KVA*	Speed, r.p.m.	x_d	x_q	x'_d	x''_d	T'_{d_0}, sec.
40,000—100,000 (average values)	62.5—100	0.63—0.89	0.45—0.59	0.27—0.32	0.21—0.26	4.4—7.2
123,500 (Kuibyshev)	68.2	0.51	0.32	0.2	0.14	5.3

The reactances, inertia constant and excitation parameters of the generator had to meet increased requirements because of power transmission over a distance of approximately 1,000 km from Kuibyshev to Moscow. In order to provide for stable operation of the system, the synchronous reactance was lowered to 0.51 and the transient reactance to 0.2. The mechanical time constant was raised to 16 sec. ($GD^2 = 121{,}000$ tm^2).

3. THE CONSTRUCTION OF HYDROELECTRIC GENERATORS

Hydroelectric generators, in the course of the 30-year history of their construction in the U.S.S.R., have been considerably changed. The first units for the Volkhov development had cast stator and rotor frames. At the present time these frames are completely welded. The load on the thrust bearing has increased from 290 tons for the Volkhov units to several thousand tons for the new hydroelectric units. This has required not only an increase in size of the thrust bearing but also considerable improvement in its construction. In particular, the thrust bearing is now self-lubricated, which provides for uninterrupted operation of large machines. The stator winding has also been considerably changed. The one-layer coil-wound stator winding used in the first units has been replaced by the 2-layer wave type bar winding of the modern generator, which has several advantages over the coil-wound winding. The electrical industry in the Soviet Union uses both suspension and umbrella type hydroelectric generators.

The selection of one or the other type is determined by the following considerations.

From the standpoint of mechanical stability and accessibility of the individual parts of the unit, the suspension type machine is preferable. For this reason, this type is used as long as it can be manufactured without a great deal of production difficulties. The use of the suspension type unit is limited by its diameter and load on the thrust bearing. Its use is also determined by the possibility of manufacturing and transporting the bearing support bracket which carries the load of the thrust bearing.

For very large stator diameters and very heavy loads on the thrust bearing, it is expedient to use the umbrella type unit, which greatly reduces the span of the supporting bracket and permits its construction from parts that can be easily transported without unduly complicating and burdening it.

As the electrical industry in the Soviet Union manufactures in the main large-sized hydroelectric units with heavy loads on the thrust bearing, the umbrella type unit, improved in the past few years, is produced mostly.

The hydroelectric generator with a rating of 68.8 *MVA*, 1940 production (see Fig. 1), has the following relatively complicated design: the rotor has curved arms; the bearing support bracket contains in its central portion the most loaded part of the support and an oil bath for the thrust bearing; the thrust bearing containing rotating shoes is supplied with a special adaptor of complicated design for purposes of disassembly and a special electromagnet for starting.

The hydroelectric generator with a rating of 71.5 *MVA*, 1952 production (see Fig. 2), has a simpler construction of the rotor and bearing support bracket. The thrust bearing with an oil bath is removed from the main part of the support and made easily accessible for inspection and disassembly. The guide bearing is located under the thrust

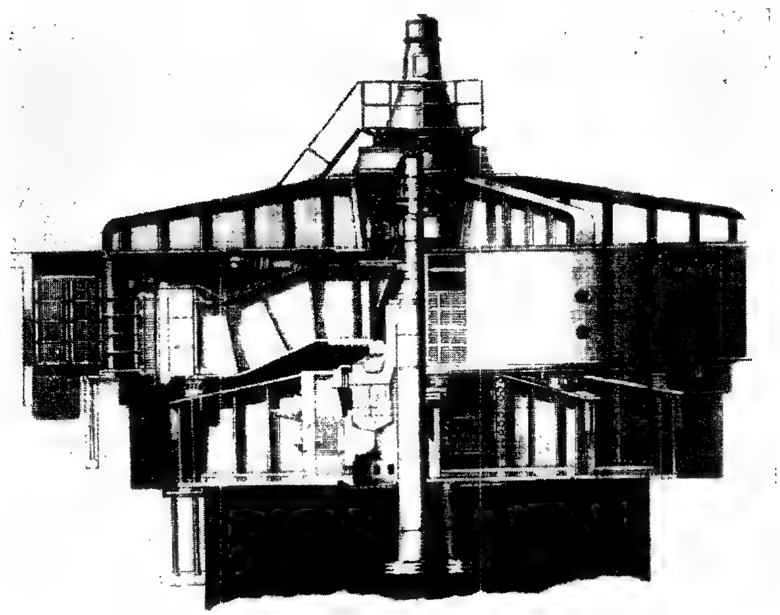

Fig. 1. A hydroelectric generator, 1940 production.

bearing. The height of the unit is reduced by using stepped arms on the lower bearing support.

Finally, the hydroelectric generator with a rating of 123.5 *MVA*, 1953 production, is a new improvement of the umbrella type unit (see Fig. 3). In this unit the thrust bearing support is not mounted on the upper bracket, which greatly simplifies its construction and reduces its height and weight. In spite of several complications in the construction of the turbine plate on which the thrust bearing support bracket is mounted, this construction, as a whole, greatly reduces the height and weight of the unit as well as the cost of the power house.

This construction differs from the previous constructions of the umbrella type unit also in the location of only one guide bearing on the upper spider. For this type of unit, the most advantageous location of the guide bearing is as mentioned above. In the first place, the upper spider is used without additional reinforcement for the transmission

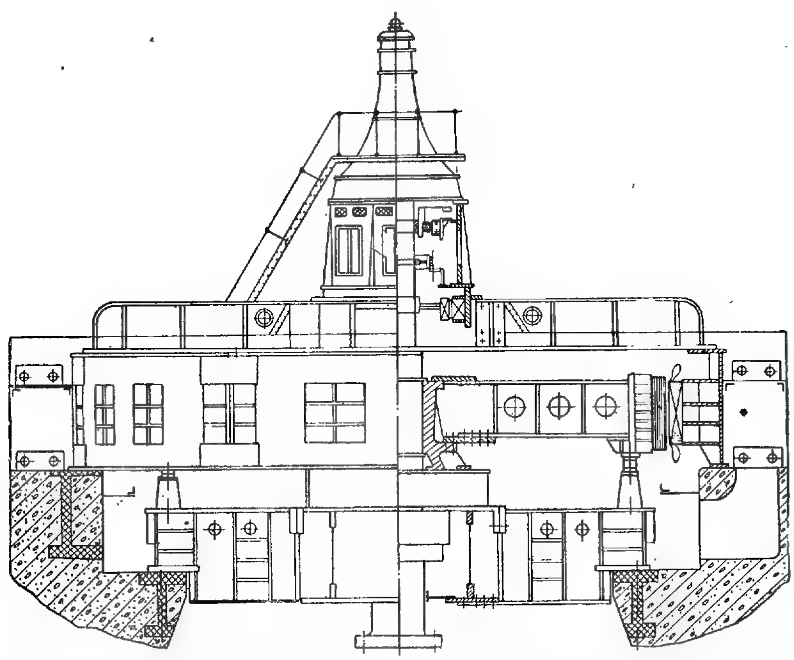

Fig. 2. An umbrella type hydroelectric generator, 1952 production.

of radial forces from the guide bearing to the foundation; and, in the second place, both guide bearings of the unit (the generator and turbine bearings) are located most advantageously from the standpoint of mechanical stability of the shaft.

The principles which are used as a basis in the design of umbrella type units in the Soviet Union are also used in the design of the suspension type units. A large suspension type hydroelectric generator is shown in Fig. 4. Here, also, the thrust bearing is located beyond the most loaded part of the bearing support bracket.

The rotor of the hydroelectric generator. It is expedient in slow-speed high-capacity machines to increase the diameter of the rotor to a value limited by the mechanical strength of the rotor at runaway speeds. By increasing the diameter of the rotor, the machine can be cooled better and

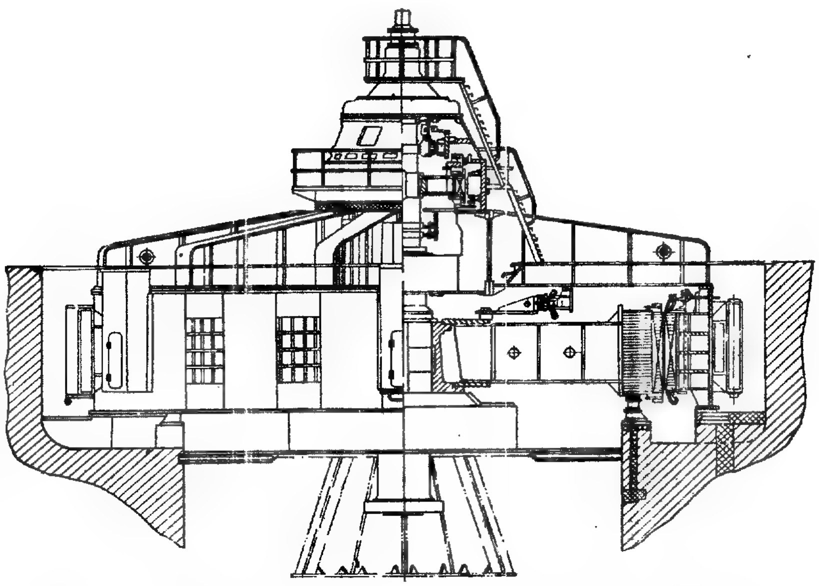

Fig. 3. An umbrella type hydroelectric generator with thrust bearing on top of the turbine, 1953 production.

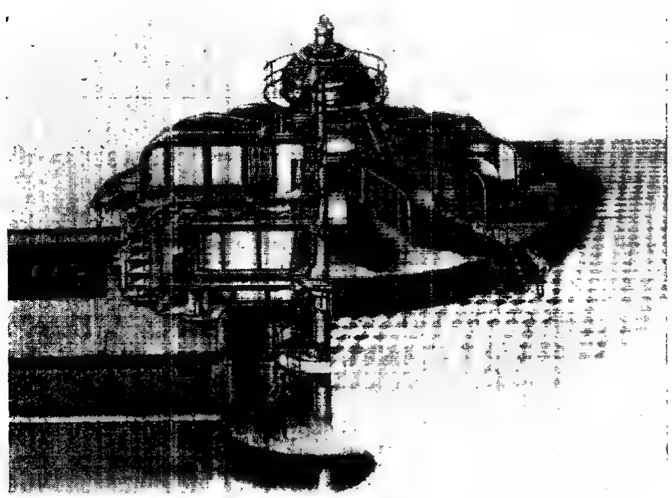

Fig. 4. A 103,500-KVA, 13,800-V, 83.3-r.p.m. hydroelectric generator.

the weight of the rotor rim reduced for a given inertia. In this respect, reducing the runaway speed of the unit considerably reduces the cost of the machine.

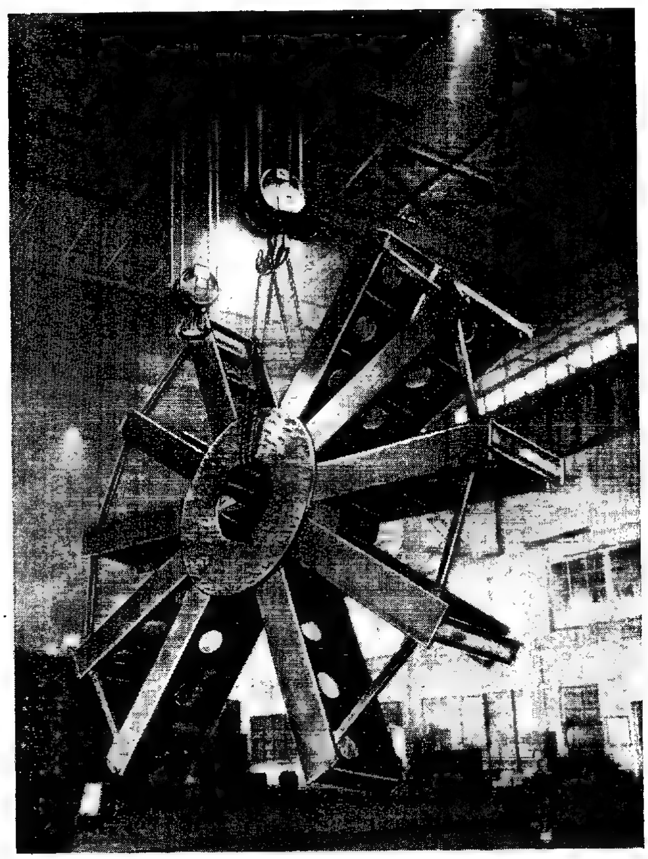

Fig. 5. A spider type rotor frame.

The diameter of the rotor frame can reach 10 m and more, therefore it should be designed for transportation in parts. There are two types of construction for rotor frames, the disk and spider types, which can be assembled from separate parts. The type used is determined by the diameter of the rotor frame. For diameters up to 4 m, one-piece disk

frames are used, for diameters up to 8 m, disassembled disk frames are used, and for diameters more than 8 m, disassembled spider frames are used. Disk type rotor frames are the simplest type and easily carry the applied torque. Spider type disassembled frames are more cumbersome because each arm bolted to the rotor rim (see Fig. 5) is designed to

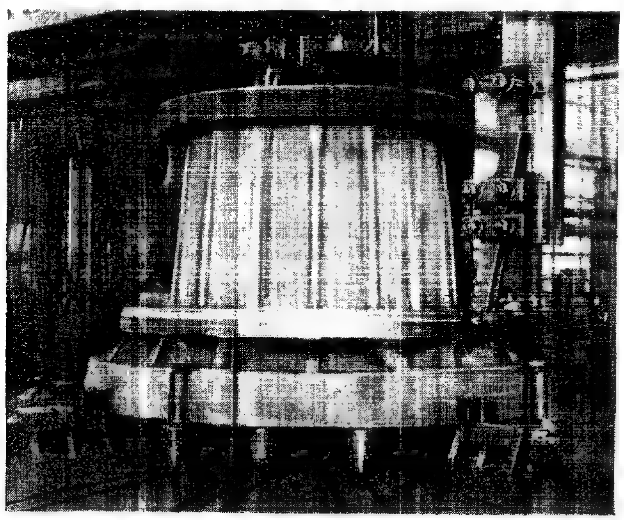

Fig. 6. A hub of a spider type rotor of a large hydroelectric generator.

carry a part of the applied torque. A hub of a spider type rotor for a large hydroelectric generator is shown in Fig. 6.

The diameter of the rim does not allow for its transportation in one piece (with the exception of rims of small hydroelectric generators); therefore, it is designed to be assembled from stamped segments.

Appreciable deformation of the rim arises from centrifugal forces because of its large diameter and high stresses in it. This deformation may reach several millimetres on a diameter for runaway speeds and may cause a shift in the centre of gravity of the rotor and vibration. Therefore, meas-

ures are taken to insure that the rim will always be centered about the shaft. This can in some way be accomplished by wedging cross-pieces into the preheated rim.

In high-speed hydroelectric generators the rotor rim and frame are combined into one (see Fig. 7). In this case the body of the rotor is made up of thick steel sheets and is

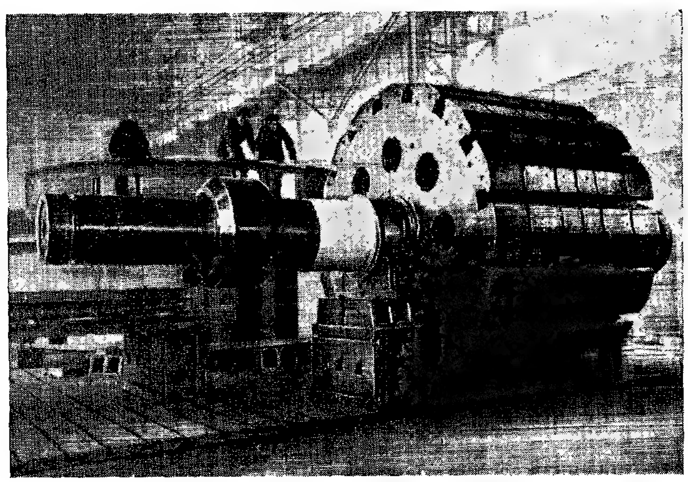

Fig. 7. A rotor of a high-speed hydroelectric generator.

machined for fitting upon the shaft and for mounting of the poles. In small-sized generators cast steel frames are used and the field poles are mounted with bolts. The poles are attached to the stamped rotor rim by T- or V-dovetails.

The design of the excitation winding of hydroelectric generators differs from that of synchronous machines in that a higher strength insulation is used. This is necessary considering that it is very difficult to replace the poles of the generator in case the insulation fails and that the voltage is increased under conditions of forced excitation.

Hydroelectric generators in most cases have damper windings on the rotor for reducing overvoltages from non-symmetrical faults on the generator and also for increas-

ing damping torques and making possible self-synchronization of the machine.

The stator (see Fig. 8). The stator body is welded from steel sheets. The frame and magnetic core consist of individual sections when the diameter is more than 4 m. The core is very securely mounted on the frame so as to pro-

Fig. 8. A section of the stator body of a large hydroelectric generator.

vide for dependable operation of the stator. The connection is calculated so that thermal stresses will be allowable.

The stator winding is usually designed for the standard 6.3- and 10.5-*KV* voltages, however, in large hydroelectric generators, because of high currents, the voltage is increased to 13.8 *KV* and higher. For dependability, bar windings with two effective conductors per slot are used in large hydroelectric generators. For medium-sized generators, coil-wound windings with more than two effective conductors per slot can be used.

As a rule, the winding insulation consists of a continuous mica tape that is compound treated under pressure after vacuum drying. This insulation well withstands mois-

ture and is little damaged by corona. For purposes of reducing corona and protecting the outside layer of insulation, the coils in the slots and end connections are covered with semiconductor varnish.

The bearing support brackets. The bearing support bracket is made stiff and strong enough so as to keep the spinning

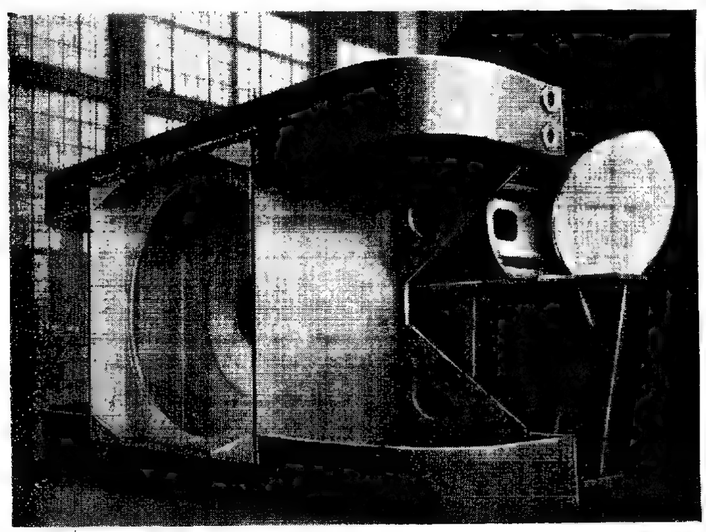

Fig. 9. A parallel-girder type support bracket.

rotor in a stable position. If possible, it should also make the thrust and guide bearings accessible without disassembling the machine.

Parallel-girder type support brackets are made in the shape of a beam with a complicated cross-section that lies on two supports (see Fig. 9). This type of support bracket is easy to manufacture and has a very simple load and deflection diagram. The stresses in the welded seams are not very large. However, with the increase of the shaft load and bending moments it becomes difficult to maintain symmetrical deformation in all directions of the part of the support bracket that serves as a foundation for the thrust bearing.

Improper distribution of the load between the shoes of the thrust bearing may result from these non-symmetrical deformations. As a consequence, for large loads a spider type bearing support bracket is used which has symmetrical deformations.

Spider type support brackets can be either simple or complex. The simple type merely acts as a support for the thrust bearing of the hydroelectric generator shown in Fig. 2. The complex type in addition has a built-in oil bath for the thrust bearing of the generator shown in Fig. 1.

From the standpoint of design and manufacture, the simple type support bracket is preferable. From the standpoint of operation the simple type is preferable as well inasmuch as the thrust bearing is easily accessible. However, complex support brackets are used for the purpose of reducing the height of the unit. They shorten the unit approximately by the height of the thrust bearing. Both types of support brackets require about the same amount of steel.

There are also two types of support brackets for guide bearings that do not carry shaft loads: girder and spider type brackets. The latter has a stronger construction that equally withstands radial forces in all directions.

The length of the main part of girder type support brackets falls within the maximum railroad dimension. Therefore, as a rule, girder type brackets have no detachable joints. Spider type brackets have detachable arms for transportation purposes.

The thrust bearing. The largest thrust bearings in the world are produced in the Soviet Union. For many years thrust bearings have been operating faultlessly with a load of 1,000 tons and a speed of 83 r.p.m., a load of 1,500 tons and a speed of 68.2 r.p.m., and a load of 2,100 tons and a speed of 62.5 r.p.m. Thrust bearings are being constructed for the hydroelectric generators of the new Volga developments that carry a load of 3,500 tons.

The production of thrust bearings carrying such loads and having outside friction surface diameters up to 4,300 mm

creates several new problems which under smaller load conditions do not play such an important role. Some of these problems are as follows:

1) reduction of thermal and mechanical deformations;
2) feeding of oil along the entire friction surface;
3) providing for oil circulation in the bath for effective cooling of the friction surface;
4) prevention of aeration of the oil.

In addition, many purely technical problems arise, such as clean and extremely accurate finishing of large surfaces, coating of large areas with an anti-friction alloy, and several others.

The most important problem is to reduce the thermal and mechanical deformation of the thrust bearing shoes. This can be accomplished by increasing the thickness of the shoes as well as by reducing their width and length.

In umbrella type units the thrust bearing is taken apart without the use of a crane. Therefore, it is important that the shoes have small dimensions. Consequently, a thrust bearing with shoes distributed in two concentric rows is used (see, for example, the thrust bearing of the generator in Fig. 1).

The guide bearings. Shoe type guide bearings of vertical shaft units insure the formation of an oil film. This type of guide bearing is most expedient from the technological standpoint for large shaft diameters. It is also very easy to assemble. Therefore, hydroelectric generators are supplied with shoe type guide bearings.

Lubrication. Lubrication of the thrust and guide bearings is accomplished without circulation of oil outside of the oil baths. The oil is circulated by the pumping action of the rotating parts of the bearing without resorting to external pumps and piping. This is the most reliable way of lubricating. The oil is cooled by special coils built-in in the oil bath.

Cooling. Large hydroelectric generators are constructed with a closed cycle self-ventilating system. As a rule, the

poles of the rotor and the axial and centrifugal blowers create a pressure necessary for the circulation of air in a closed cycle.

Artificial ventilating schemes with installation of fans were rejected so as to keep the efficiency (reliability) of the hydroelectric generator high.

The large diameter of the generator and the complications involved in stopping the leakage of air from the air duct make the installation of any artificial ventilating scheme very difficult in hydroelectric generators. With the increase of the diameter and length of the active parts of the hydroelectric generator above specified limits, it may become necessary to supply cooled air along the entire length of the machine through radial ducts in the rim of the rotor.

This results in the following:

1. The cross-section of the entrance ducts for air is increased.

2. Cold air flows along the entire length of the machine.

3. Air pressure is increased as a result of the increase in the difference of peripheral velocities on the inside and outside surfaces of the rotor.

Excitation. For obtaining maximum dependability of the excitation and automatic regulation systems at the present time the exciter, sub-exciter and regulator-generator are mounted directly on the shaft of the hydroelectric generator. This system replaced the earlier used system of an auxiliary synchronous generator mounted on the shaft feeding a high-speed exciter that was mounted separately.

The exciter has a ceiling voltage and speed of voltage increase as given by technical requirements.

The exciter voltage is not standardized and is limited by its maximum allowable value taking into consideration the value of the ceiling voltage. This is done so as to lower the excitation current of the rotor. The sub-exciter, as a source of independent excitation of the main exciters, is not installed when the zone of voltage regulation of the

main exciter scheme insures stable performance for all types of operating conditions.

Thus, the normal excitation system of the hydroelectric generator consists of the following machines:

1) the main exciter having wide voltage regulation with an independent excitation;

2) the sub-exciter with D. C. voltage for the excitation of the exciter.

In the past few years a contactless system of regulation of the excitation has been extensively used with the aid of compounding from current transformers and a two-system corrector that regulates voltage. It became expedient to change to a system of partial self-excitation of the main exciter so as to utilize the amplifying action of the latter. The quick response of this system is obtained either by a machine-amplifier or by relay-contacting devices that switch resistance in and out of the excitation circuit of the exciter.

Recent stability investigations of extra long distance transmission systems called for a fundamental re-examination of the excitation system so as to provide for more reliable machine operation with high ceiling voltages and for obtaining the quickest possible response of the system.

In accordance with these requirements it was found necessary to do the following:

a) to change the principle of regulating the excitation;

b) to limit the voltage on the field brushes of the excitation system.

For a regulating system with a high ceiling voltage (3 or 4 times normal) it became necessary to use a two-machine excitation system. One of the machines operates with a D. C. voltage V and the voltage of the other machine (the booster) connected in series with it is varied from $-V$ to $+V$. Therefore, voltage on the slip rings of the rotor can be regulated from 0 to $2V$ where $2V$ is called the ceiling voltage of the exciting system.

Special attention in the regulating system should be given to the connection of the booster so as to provide for reliable operation and quick response. It is most expedient to use as a booster a separately located motor-generator set driven by an induction motor that in its turn is fed from an auxiliary generator mounted on the shaft of the main generator.

This excitation system is used for the generators of the Kuibyshev hydroelectric station. It provides for a maximum ceiling voltage of 1.600 V on the slip rings of the rotor with a time constant of the excitation winding of the booster equal approximately 0.1 sec. Regulation of the booster excitation comes from a thyratron regulator.

A regulator-generator is used to feed the drive of a pendulum regulator of the turbine. It consists of a synchronous generator with permanent magnets. A regulator-generator has a small air gap. Therefore, as a rule, it is mounted on the ball bearings and connected to the shaft of the main generator by means of an elastic coupling.

CONCLUSIONS

1. Hydroelectric generators built in the U.S.S.R. and operating in the powerful hydroelectric stations on the Volga are the largest units of their kind in the world with respect to torque, load on the thrust bearing, and size.

2. The hydroelectric generators built in 1953 for the Kuibyshev station are a further development in the production of large slow-speed machines.

3. The above-mentioned particularities of hydroelectric generators are caused by the specific type of the hydro potential of the country and the large scale of hydroelectric construction in the U.S.S.R.

4. The vast expanses of the Soviet Union and the expediency of interconnecting power systems require the solution of problems concerning long distance power transmission. This, in its turn, increases the requirements that the generator parameters and excitation system have to meet.

5. The work done in connection with the construction of generators for the Kuibyshev station makes one confident in the possibility of the successful design of even larger 200—250-*MVA* slow-speed hydroelectric generators for hydro developments on the Siberian rivers projected in conjunction with the plan for the electrification of the U.S.S.R

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LARGE POWER SYSTEMS OF THE USSR — THE MOST IMPORTANT SOURCE OF ELECTRIC POWER FOR AGRICULTURE

by
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The inculcation of industrial methods in electrified agriculture requires an uninterrupted supply of stable electric energy. Large power systems are becoming the most important source of electric power for agriculture in the USSR.

The connection of rural installations to large power systems gives rise to numerous new technical problems such as the selection of voltages for rural distribution networks, cost reduction of networks and electrical equipment, voltage regulation and protection.

Economic solutions of these problems are proposed on the basis of an analysis of the particularities of rural electrification in the USSR.

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INTRODUCTION

The extensive development of planned rural electrification carried out over the vast territory of the USSR and embracing many thousands of large farms makes high demands on sources of electric power.

At the end of 1953, 95 per cent of all machine and tractor service stations in agriculture were electrified as were 90 per cent of all government farms and over 20,000 large collective farms. Electricity is being more and more used in agriculture. It is coming into use even for such labour-consuming work as the tilling of the soil. In 1953, more than 300,000 motors with ratings from $^{1}/_{2}$ to 50 kw were used in the operation of agricultural machinery. In five machine and tractor service stations located in different sections of the country, 100 electric tractors driven by traction motors having a rating of 42 kw and a nominal voltage of 1,000 v are in operation.

The inculcation of industrial methods in electrified agriculture (production lines, hourly schedules, etc.) requires an uninterrupted supply of stable electric energy. This requirement can be completely satisfied only by large power systems and to a much smaller extent by individual small power stations not connected into a network with other power stations.

Accordingly, at the present time the construction of rural hydroelectric stations with ratings up to 50 kw has been discontinued, and in its stead larger hydroelectric stations with ratings of [illegible],000 kw and more are being constructed. The newly constructed stations are connected with the ones already in operation into rural electric systems. As a result,

the production of electric energy of the stations as well as the reliability of its supply to the rural consumer are increased while at the same time its cost is reduced.

With the same purpose in mind, agricultural loads are all the more being connected to large systems that are operating in all the important areas of the USSR. The energy supplied by large power systems has always constituted a high percentage of the total energy supplied to agriculture. Table 1 gives the relationship of the various types of bulk power sources supplying agriculture as of 1953.

TABLE 1

Type of bulk power source	Values in per cent
Rural hydroelectric stations	16
Rural power stations	44
Connection to non-rural power stations	40

The main technical and economic advantages of electrification by supplying the agricultural consumer from large power systems are as follows:

1. The agricultural consumer is provided with reliable and stable service (constant frequency and voltage).

2. The cost of energy in this case is lower than in any other case.

3. The capital investment made by the agricultural consumer for the connection of his load to the power system is noticeably less than that necessary for the construction of a rural station.

4. The time necessary for electrification is considerably reduced.

5. The agricultural load being small in comparison with the capacity of a large power system does not essentially affect the performance of the latter.

The above-mentioned advantages of electrifying agriculture by supplying energy from large power systems were fully proved during the electrification of agriculture in sev-

eral sections of the country where large power systems were accessible (such as the Moscow, Leningrad, Dnieper, Ural and other systems). In these sections of the country there are more electrified farms than in any other. It is also in these sections that the electrification of farm implements is being carried out most successfully. On the average there are about twice as many motors operating on each collective farm supplied by a large power system as there are on a farm supplied by a small rural station.

The successful fulfilment in the USSR of the plan for the electrification of the entire country and as a consequence the extensive construction of large hydroelectric stations make it all the more possible to connect agricultural loads to large electric stations. This primarily refers to the Kuibyshev, Stalingrad, Kakhovka and other hydroelectric stations that are now under construction.

Large power systems that contain sizable hydroelectric stations are already at the present time the most important source of electric power for agriculture. In the future their role in the electrification of farm implements will become still more important and decisive. The rapidly developing agricultural load in its turn will begin to noticeably affect the operation of large power systems.

Some technical problems related to the supply of agricultural loads by large power systems will be considered below in order to take into account all their particularities when solving technical problems concerning the development of large power systems and long distance transmission at high and extra high voltages.

I. THE DENSITY OF THE RURAL LOAD

Rural electrification in the USSR where agriculture is evenly spread over the vast territory of the country and where collective farms consist of large tracts of land (on the average a collective farm in the USSR has 1,693 hectares of tillable land) is characterized by a sparseness and

relatively low power of the consumers. This condition in the final analysis creates a very low load density. Only in sections where electric ploughing is widely practised and where big electric pumping stations are used for purposes of irrigation is the rural load density somewhat increased.

Experimental and calculated data of highly electrified rural sections of the country make it possible to determine the rural load density which is computed in accordance with peak values on the distribution transformer buses of the consumer being approximately as given in table 2.

TABLE 2

Type of load	Load density in kw per sq. km.
Electrification of stationary farm implements and homes	2
Electrification of mobile farm implements in the field	3
Electrification of irrigation from local water-supply sources (10 per cent of all land is irrigated)	2
Electrification of agriculture as a whole taking into account the total load curve	5

The total amount of agricultural power consumption is determined by superposing the load curves of the individual groups of consumers. The yearly peak of the load curve for stationary farm implements and homes occurs in wintertime. In summertime, when peak irrigation loads are added to loads that constitute approximately 35 per cent of the above-mentioned peak load of stationary farm implements, the total peak load approaches or even surpasses the winter peak. If electric ploughing is practised, the yearly peak agricultural load undoubtedly shifts to the summer months when all types of agricultural loads are jointly consumed.

If vast areas are irrigated from big rivers by means of large pumping stations that already constitute a concentrated load, the peak agricultural load in summertime is further increased.

II. SELECTION OF VOLTAGES FOR RURAL DISTRIBUTION NETWORKS

The selection of voltages for rural distribution networks is becoming an especially important problem considering that rural loads are being extensively supplied by large power systems.

At the present time the distribution voltage in rural areas is 10 kv. Sub-transmission circuits have a voltage of 35 kv. The capacity of distribution transformers having a step-down voltage ratio of 10 kv/400 v as a rule is 50 kva. There are three or four such transformers that supply a rural load area of 100 sq. km. when the load density is 2 kw per sq. km.

Until recently the length of the 10-kv distribution line was about 15—20 km, which was computed only on the basis of the voltage drop. The economical current density of the conductor was not calculated, and as a result the cross-section of the conductor was 2.5 to 5 times as great as its economical value.

The range of the transformer substation with a step-down voltage ratio of 35/10 kv is limited to 20—25 km.

In feeding agricultural areas from large power systems through several voltage levels the above-mentioned allowable length of distribution lines (10 kv) is no longer permissible inasmuch as it results in a considerable waste of metal. Calculations show that in this case the range of the 10-kv lines should be approximately halved. However, even then the current density of the distribution line will be 1.5 times less than the economical density.

The above-indicated features of distribution lines (10 kv) determine to a great extent the constants of distribution substations (35/10 kv). The values of these constants are given in table 3.

An analysis of different types of 35-kv distribution circuits made possible the selection of constants for 35- and 110-kv circuits that are given below in table 4. In this analysis it was granted that the agricultural load was on the whole evenly spread throughout the area and that the power factor

The TWG scheme has been widely used in three-phase high-voltage rural networks. At the present time more than 10,000 km of rural lines are operating according to this scheme. In some sections of the country, as for example in the Georgian SSR, more than half of all high-voltage rural networks is operating according to the TWG scheme in which 33 per cent of conductors and insulators are saved.

However, the interference caused by such TWG power circuits on adjacent communication lines is increased severalfold. This is especially true in the case of one-conductor lines. Considering the fact that one-conductor lines are being gradually replaced by two-conductor and cable communication lines this difficulty in the use of the TWG scheme is being eliminated. A detailed study of the performance data of rural TWG networks conducted by the Tbilisi branch of the All-Union Institute for the Electrification of Agriculture showed the advantages of the scheme even in unfavorable soil conditions and in case of line construction in mountainous regions.

According to the USSR standards and regulations for rural electrical installations, protective and operational groundings of distribution substations in TWG circuits are combined into one. A grounding resistance of not more than 4 ohms is used if the total transformer capacity of the substation feeding the TWG circuit is not more than 3,200 kva. If the transformer capacity is more than that, the grounding resistance should not be more than $^1/_2$ ohm.

When feeding TWG circuits from large power systems further investigation is necessary to determine the size of the grounding resistance and the possibility of its increase.

While the TWG scheme makes possible the economizing of conductors only in high-voltage networks, it is possible to achieve considerable economy in low-voltage networks by using in the rural areas the three-phase — one-phase scheme of distribution. It is worthwhile to note that almost 75 per cent of all wire used in rural electrical installations goes for low-voltage networks.

In the three-phase—one-phase electrical distribution scheme, the high-voltage distribution line consists of three phases (with or without ground as a return conductor), and large power consumers (such as repair shops, electric tractors, pumping stations for irrigation, etc.) are fed from it. Small power consumers and lighting loads are fed from one-phase circuits that branch out from the distribution line. Therefore, power is brought right to the consumer at a high voltage, and only there it is transformed into a low voltage by small one-phase low-power transformers (3, 5 and 10 kva).

The use of the three-phase—one-phase scheme as compared with the ordinary type of distribution scheme reduces the cost of the rural distribution network by 50 per cent.

It is also possible to reduce the cost of rural distribution networks by using lighter switchgear and protective equipment. This can be done on the basis of a study of short-circuit currents in rural networks. Preliminary calculations indicate that it is possible to reduce the cost of such equipment by 1.5 to 2 times.

IV. VOLTAGE REGULATION IN RURAL DISTRIBUTION NETWORKS

At the present time, rural networks are calculated on the basis of allowable voltage deviation at the load. In accordance with this, the current density of conductors in the network is usually 2 or 3 times lower than its recommended economical value.

Voltage regulation in rural distribution networks can bring the actual current density closer to the economical one, thus resulting in a fuller utilization of the conductor.

It is worthwhile to use special network voltage regulators in circuits fed from large power systems. A simple automatic voltage regulator developed by the All-Union Institute for the Electrification of Agriculture can serve as an example.

The regulator consists of an additional low-voltage autotransformer with a power rating of 20 and 50 kva. It is possible to obtain 5 per cent voltage regulation by reversing its shunt winding. The practical use of such regulators in rural distribution networks shows that it is possible to approximately halve the conductor cross-section in low-voltage networks and thus reduce the construction costs of the network by 20 to 30 per cent. Over one ton of wire is saved by the installation of each regulator having a power rating of 20 kva.

At the present time, a scheme and a model of a high-voltage regulator have been developed. The regulation is accomplished by switching the tap connections of the transformer under load and by utilizing non-linear resistance shunts.

The possibility of voltage compensation in high-voltage rural distribution networks by a series installation of static condensers at various points in the network is also a problem that deserves serious consideration. The inertia-free response of these condensers to transient voltage fluctuations caused by the switching of comparatively large motors (e. g., traction motors used in tractors) is of great interest. However, it is necessary to investigate ways of protecting these condensers against over-voltages caused by faults on the consumer's side.

V. PROTECTION OF RURAL DISTRIBUTION NETWORKS FED FROM LARGE POWER SYSTEMS

The extensive supply of agricultural loads from large power systems requires a new approach to the problem of rural distribution network protection. Rural networks in this case become much longer and consist of more branches. It is necessary to provide for the co-ordinated operation of relay protection against faults in radial networks consisting of several sections and also to provide for the correct operation of relay protection against faults at the far end of

steel conductor lines that have large impedances. One possible way of improving the fault protection of lines is the installation of relay equipment instead of fuses on distribution lines and branch points. In connection with this, it becomes necessary to construct a cheap and light-weight high-voltage circuit breaker for the load that can be directly mounted on line towers.

In order to improve the operation of fuse and relay protection during ground faults, switches that interconnect lines can be used with relays that are sensitive to small short-circuit currents. Thus, the proper operation of the main protection is insured.

Other protection problems should also be considered from a new point of view; in particular, automatic reclosing in rural lines and protection of low-voltage rural lines against lightning.

Successful experiments that have recently been carried out in using power conductors of rural distribution networks as a means of sending high-frequency dispatcher signals make it possible to improve considerably the operation of rural installations and increase the reliability of power supply for agriculture.

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